Intensity-Frontier Experiments with Antiprotons

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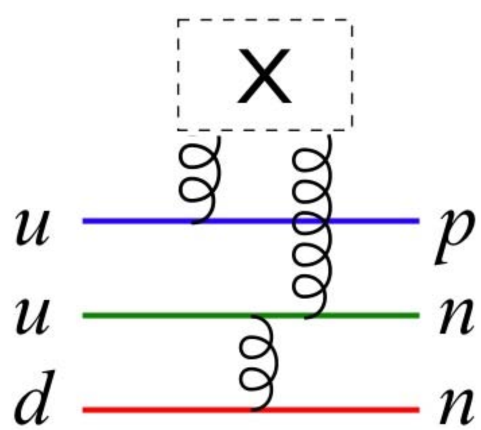


RPM Seminar
Lawrence Berkeley National Laboratory
8 November 2011

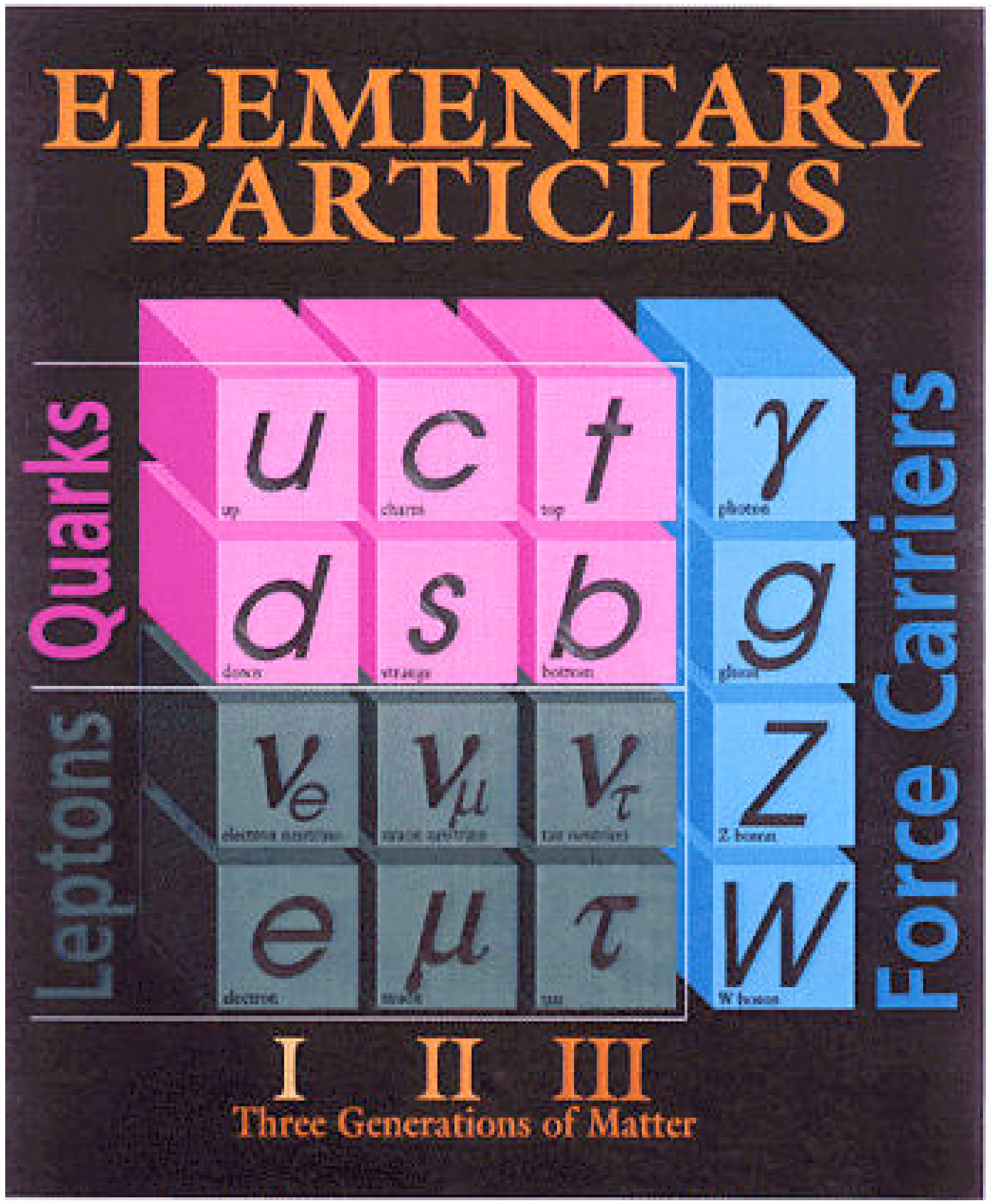
Outline

Varied menu!

- Baryogenesis and CP violation
- Hyperon CP violation
- Low-energy antiprotons
- A new experiment
- Charm & charmonium
- $\bar{p}$ Drell-Yan
- Antihydrogen
- Competing proposals for the facility
- Summary

Cast of Characters

- After many decades of experimentation with subatomic particles, we now know what everything is made of...



Baryons & antibaryons:

$p = uud$ & $\bar{p} = \bar{u}\bar{u}\bar{d}$

$\Lambda = uds$ & $\bar{\Lambda} = \bar{u}\bar{d}\bar{s}$

...

Mesons:

$K^0 = d\bar{s}$ & $\bar{K}^0 = \bar{d}s$

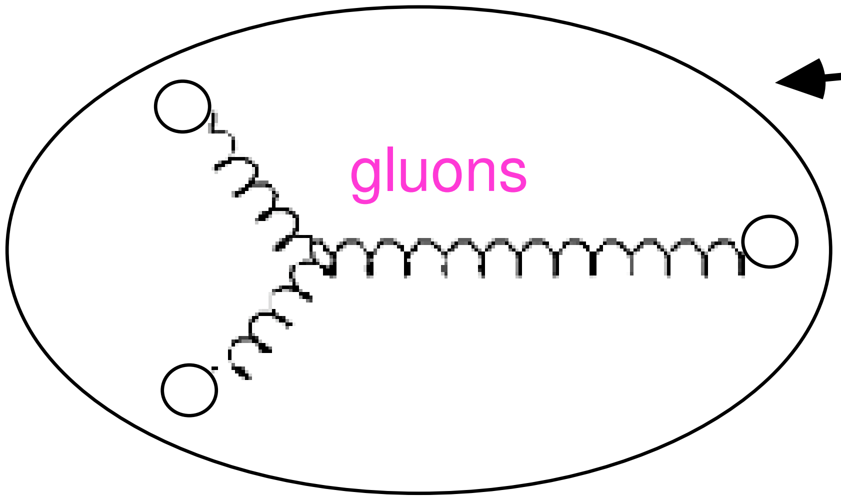
$B^0 = d\bar{b}$ & $\bar{B}^0 = \bar{d}b$

$B^+ = u\bar{b}$ & $B^- = \bar{u}b$

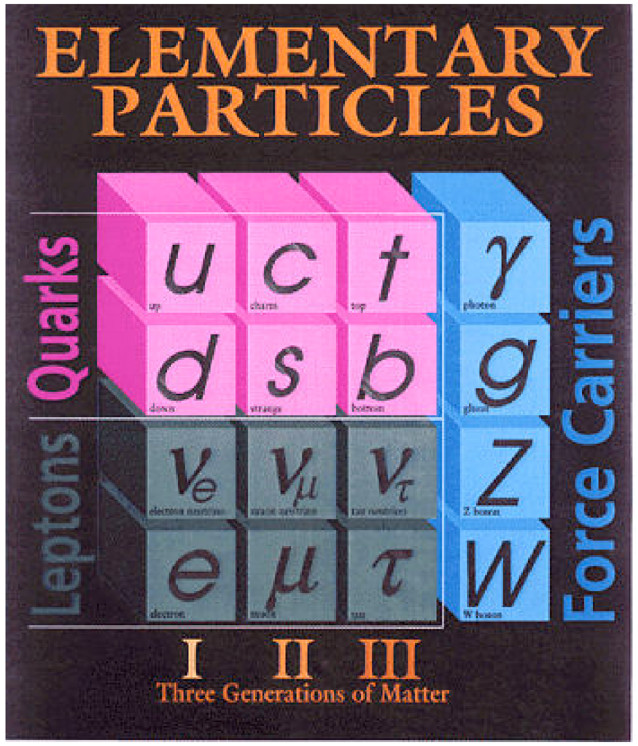
...

Cast of Characters

...and how it's held together:



3 quarks inside a proton or neutron

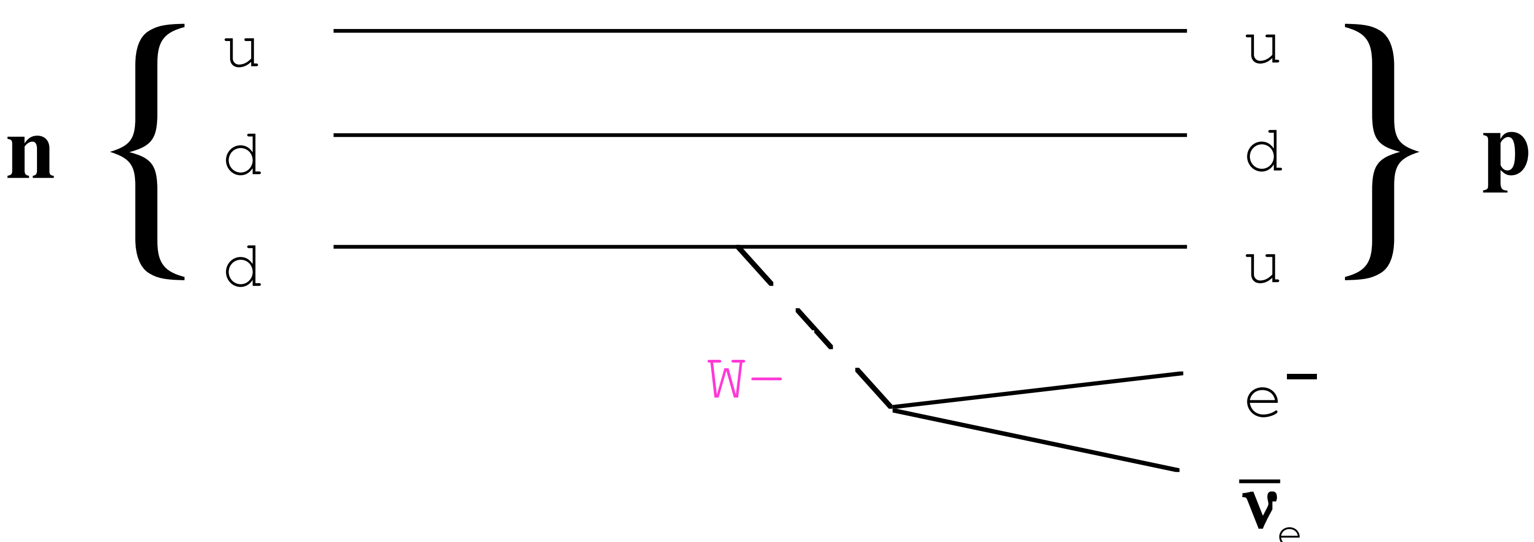


hydrogen atom:

virtual photons

...and why it falls apart:

neutron beta decay



Baryogenesis

- Universe dominantly matter, negligible antimatter
- How could matter excess have developed?
- Sakharov (1967): possible if, soon after Big Bang, there were

1. C and CP violation (⇒antimatter/matter not mirror images)
2. non-conservation of baryon-number
3. non-equilibrium conditions

- During such a period,
  - any pre-existing net baryon number would be destroyed
  - a small net baryon number would be created

CP Violation

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  - any pre-existing net baryon number would be destroyed
  - a small net baryon number would be created

CP Violation

- CPV already discovered in 1964: small effect in K^0 mixing & decay
  - nicely explained in SM by Kobayashi–Maskawa mechanism: non-zero phase in CKM quark mixing matrix
- KM model makes simple, striking prediction:
  - ➡ if CPV due to CKM-matrix phase, should be large effect in decays of beauty particles!
- CPV now observed in *B*-meson decays as well [BaBar & Belle, 2001, CDF, DØ, LHCb]

(Hence Kobayashi & Maskawa 2008 Nobel prize)

CP Violation

- CPV already discovered in 1964: small effect in
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uty particles!
  - erved in B-meson decays as well [BaBar
1, CDF, DØ, LHCb]

(Hence Kobayashi & Maskawa 2008 Nobel prize)

But insufficient to account for baryogenesis!

How else might baryogenesis arise?

What other processes can distinguish matter from antimatter?

Non-KM CP Violation

- 5 places to search for new sources of CPV:
  - Kaons
  - B mesons
  - Hyperons
  - Charm
  - Neutrinos

Years of intensive new-physics searches have so far come up empty*

Worth looking elsewhere as well!

*except for possible DØ 3.9σ dimuon signal

Hyperon CP Violation

Hyperon CP Violation

- An old topic:

PHYSICAL REVIEW VOLUME 184, NUMBER 5 25 AUGUST 1969

Final-State Interactions in Nonleptonic Hyperon Decay

O. E. OVERSETH*
The University of Michigan, Ann Arbor, Michigan 48104

AND

S. PAKVASA†
University of Hawaii, Honolulu, Hawaii 96822
(Received 1 April 1969)

⋮

E. Tests for *CP* and *CPT* Invariance

Thus in hyperon decay, $\bar{\alpha} \neq -\alpha$ implies *CP* violation in this process independent of the validity of the *CPT* theorem. This is also true if $\bar{\beta} \neq -\beta$.

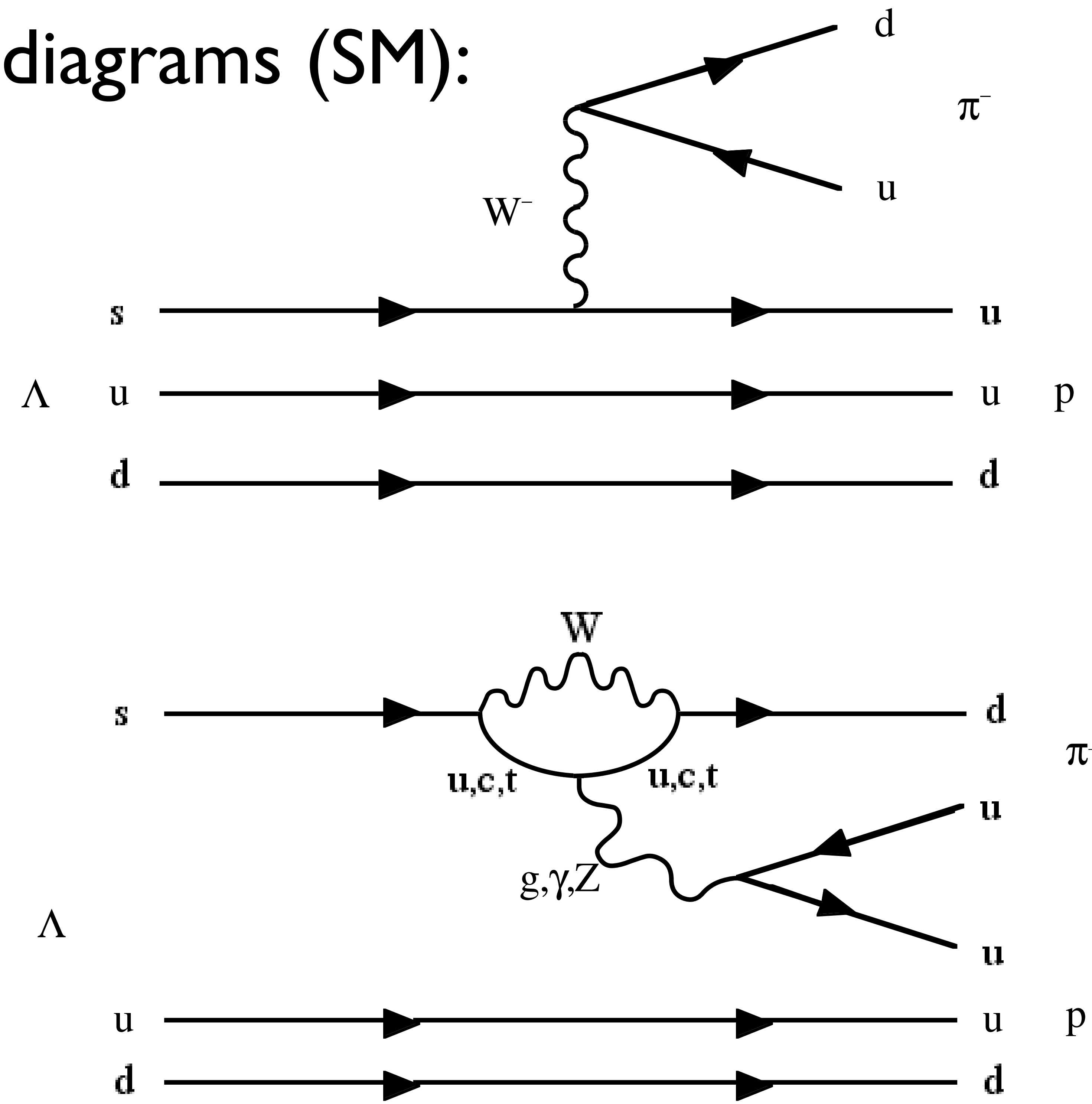
Also, as usual, *CPT* invariance implies equality of Λ^0 and $\bar{\Lambda}^0$ lifetimes, whereas *CP* invariance implies equality of partial rates $\Gamma^0 = \bar{\Gamma}^0$, and $\Gamma^- = \bar{\Gamma}^+$. This is also true when final-state interactions are included in the analysis.

Hyperon CP Violation

- Example Feynman diagrams (SM):

Λ decay:

Λ penguin decay:



- “New physics” (SUSY, etc.) could also contribute!

Hyperon CP Violation

- Hyperon decay violates parity, as described by Lee & Yang (1957) via "α" and "β" parameters
  - e.g., decay of polarized Lambda hyperons:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p)$$

⟶ nonuniform proton angular distribution in Λ rest frame w.r.t. average spin direction $\vec{P}_\Lambda$

  - size of α indicates degree of nonuniformity:

α_Λ = 0.642 (±0.013) $\Rightarrow p$ emitted preferentially along polarization (Λ spin) direction

☞ Large size of α looks favorable for CPV search!

Hyperon CP Violation

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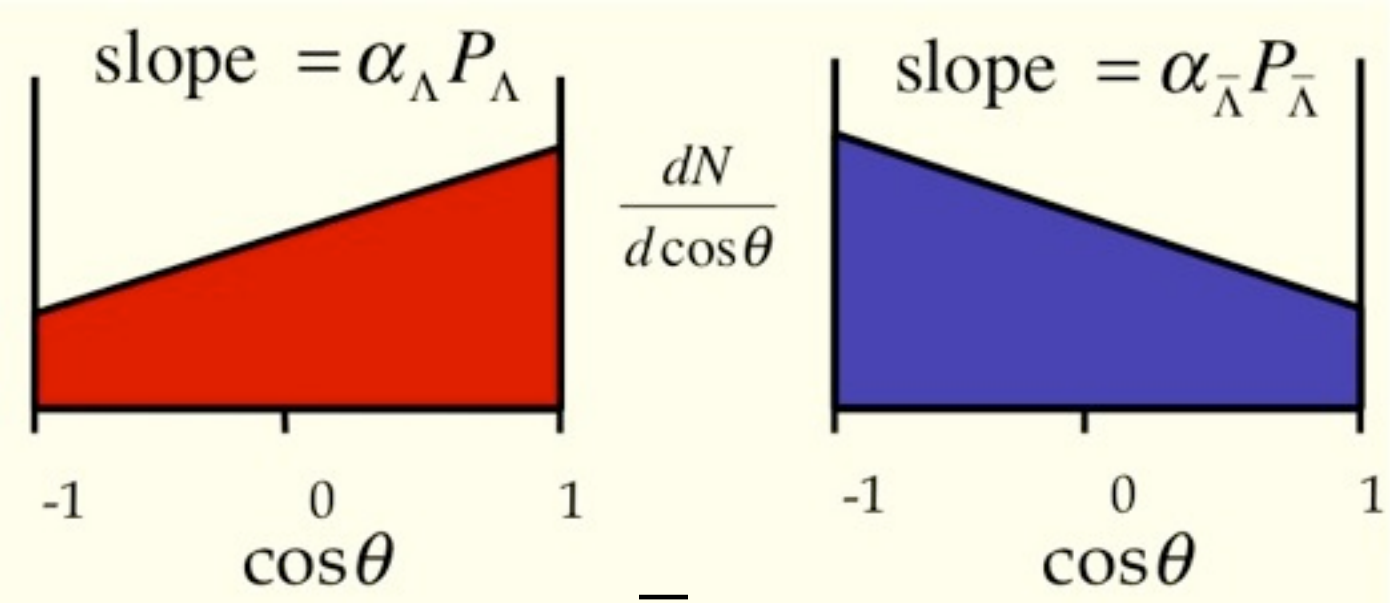
  - e.g., decay of polarized Lambda hyperons:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{q}_p)$$

$\longrightarrow$ nonuniform proton angular distribution in Λ rest frame:

$\Lambda \to p\pi^-$



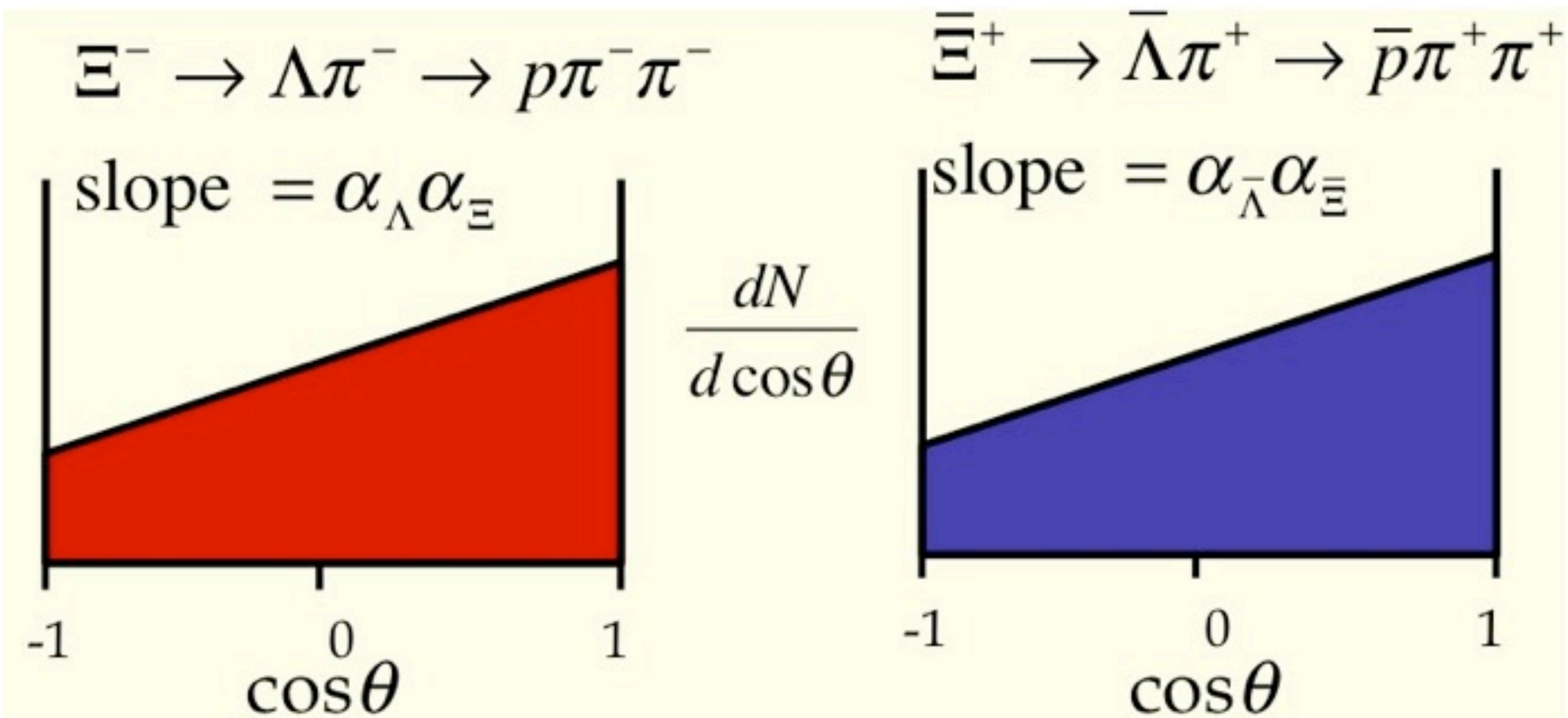
$\bar{\Lambda} \to \bar{p}\pi^+$

$$\Rightarrow A_\Lambda \equiv \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda},\ B_\Lambda \equiv \frac{\beta_\Lambda + \bar{\beta}_\Lambda}{\beta_\Lambda - \bar{\beta}_\Lambda},\ \Delta_\Lambda \equiv \frac{\Gamma_{\Lambda \to P\pi} - \bar{\Gamma}_{\Lambda \to P\pi}}{\Gamma_{\Lambda \to P\pi} + \bar{\Gamma}_{\Lambda \to P\pi}}$$ CP-odd

Hyperon CP Violation

- But, for precise measurement of A_Λ, need excellent knowledge of relative Λ and $\bar{\Lambda}$ polarizations!

➡ HyperCP "trick": $\Xi^- \to \Lambda\pi^-$ decay gives $\vec{P}_\Lambda = -\vec{P}_{\bar{\Lambda}}$



- Unequal slopes $\Rightarrow$ CP violated!

Hyperon CP Violation

- Differently sensitive to New Physics than *B*, *K* CPV
- Standard Model predicts small CP asymmetries in hyperon decay
- NP can amplify them by orders of magnitude:

Table 5: Summary of predicted hyperon CP asymmetries.

Asymm.	Mode	SM	NP	Ref.
A_Λ	$\Lambda \to p\pi$	$\lesssim 10^{-5}$	$\lesssim 6 \times 10^{-4}$	[68]
$A_{\Xi\Lambda}$	$\Xi^\mp \to \Lambda\pi,\ \Lambda \to p\pi$	$\lesssim 5 \times 10^{-5}$	$\leq 1.9 \times 10^{-3}$	[69]
$A_{\Omega\Lambda}$	$\Omega \to \Lambda K,\ \Lambda \to p\pi$	$\leq 4 \times 10^{-5}$	$\leq 8 \times 10^{-3}$	[36]
$\Delta_{\Xi\pi}$	$\Omega \to \Xi^0\pi$	2×10^{-5}	$\leq 2 \times 10^{-4}\,*$	[35]
$\Delta_{\Lambda K}$	$\Omega \to \Lambda K$	$\leq 1 \times 10^{-5}$	$\leq 1 \times 10^{-3}$	[36]

*Once they are taken into account, large final-state interactions may increase this prediction [56].

Small sizes of $(A,\Delta)_{SM}$ favorable for NP CPV search!

Hyperon CP Violation

- Measurement history:

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	**-0.02 ± 0.14**	[P. Chauvat et al., PL 163B (1985) 273]
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 ± 0.10**	[M.H. Tixier et al., PL B212 (1988) 523]
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	**0.006 ± 0.015**	[P.D. Barnes et al., NP B 56A (1997) 46]

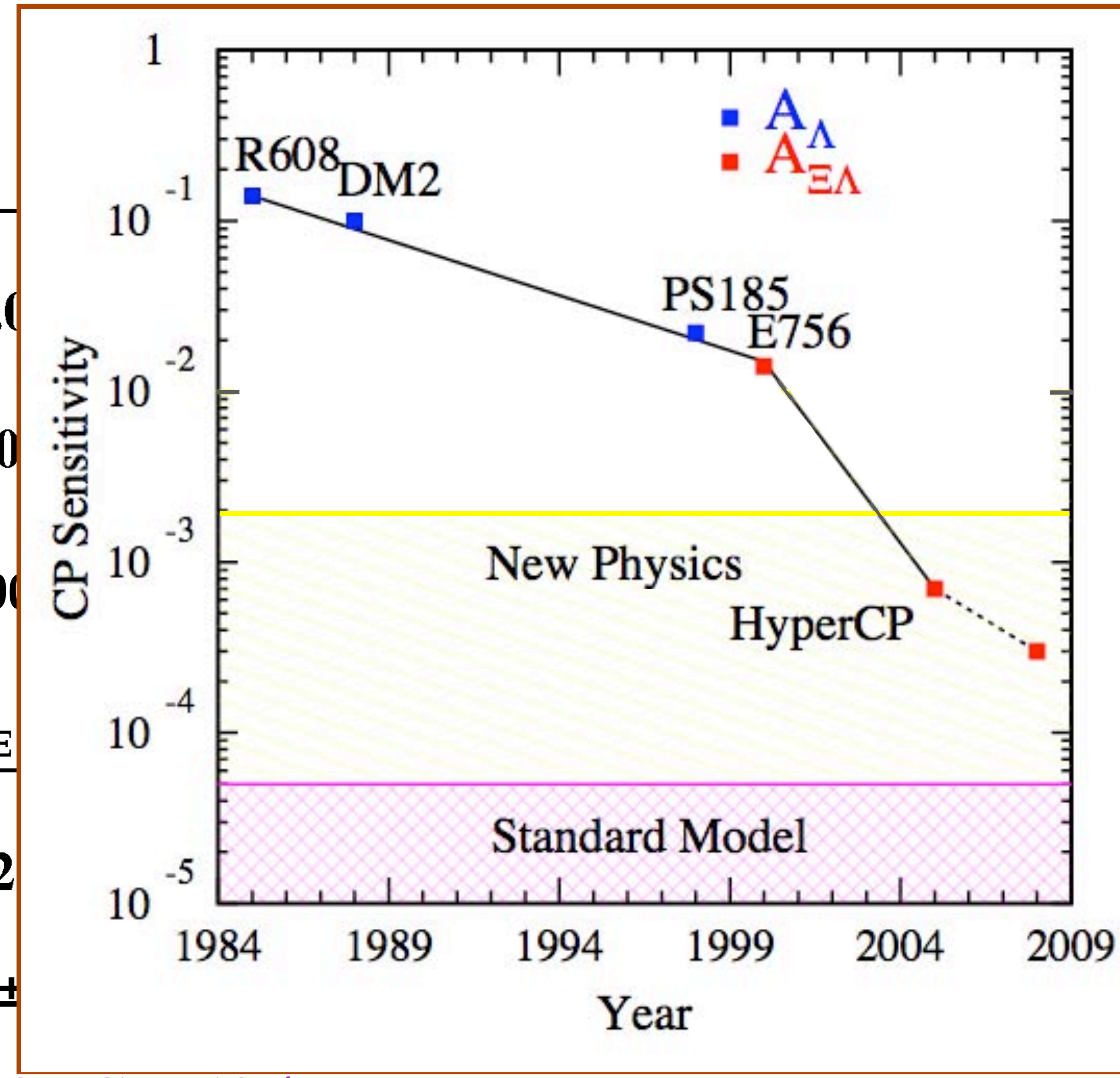
Experiment	Decay Mode	$A_\Xi + A_\Lambda$	
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**0.012 ± 0.014**	[K.B. Luk et al., PRL 85, 4860 (2000)]
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	**$(0.0 \pm 6.7) \times 10^{-4}$**	[T. Holmstrom et al., PRL 93. 262001 (2004)]
		$(-6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary; PRL in prep]

Hyperon CP Violation

- Measurement history:

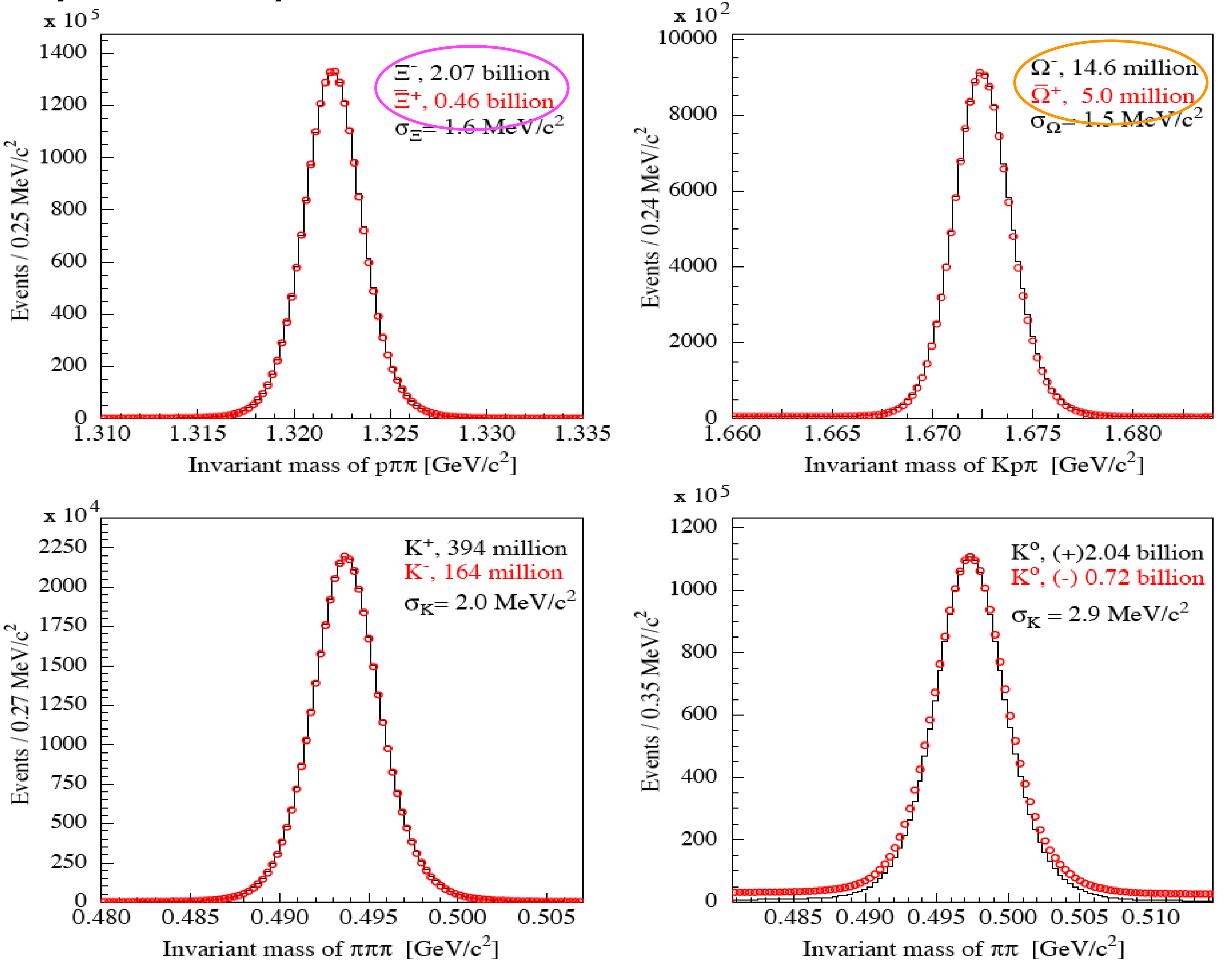
Experiment	Decay Mode	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-0.0
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.0
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	0.0

Experiment	Decay Mode	A_Ξ
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	0.012
E871 at Fermilab (HyperCP)	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	(0.0 ±

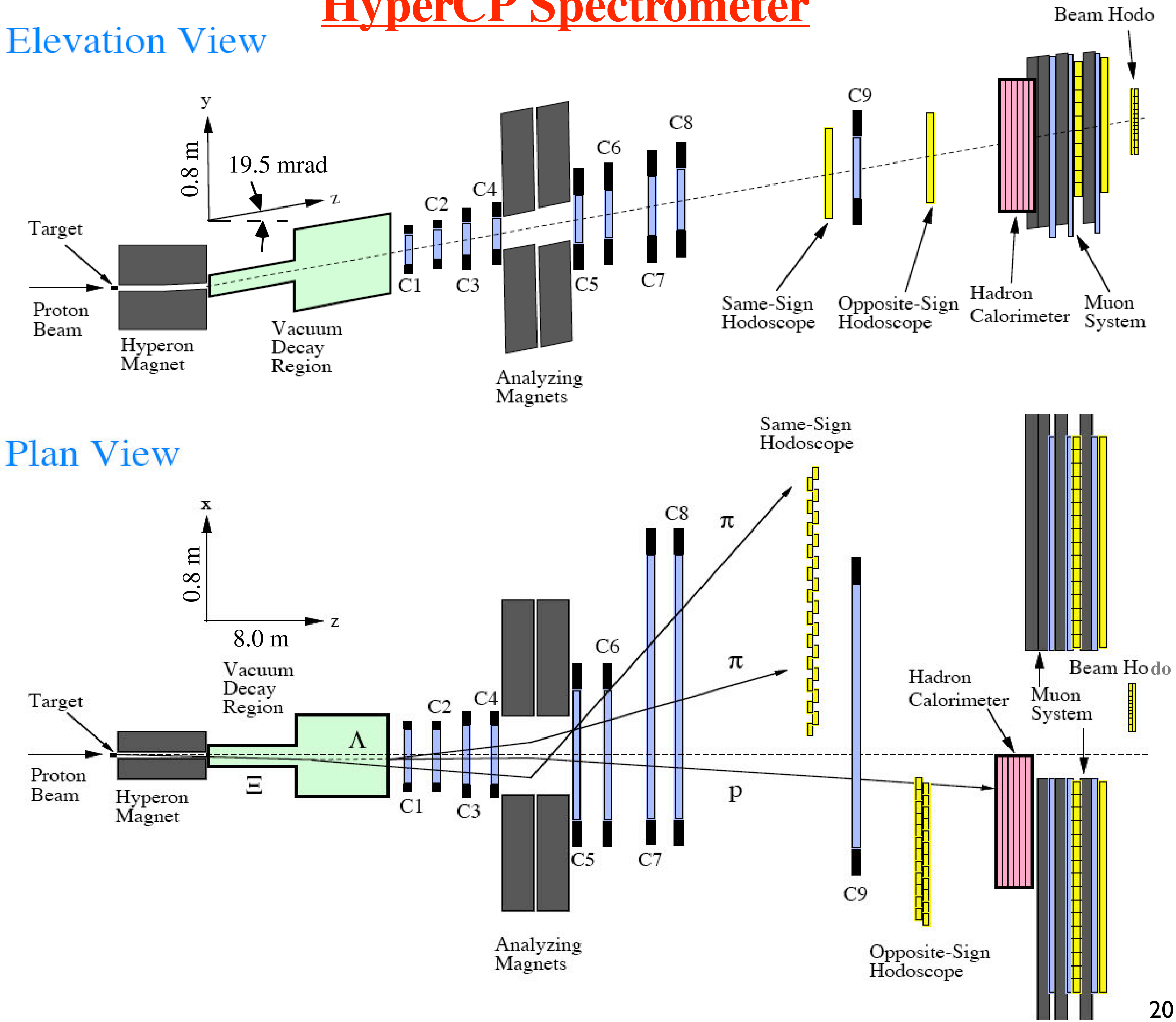


$(-6 \pm 2 \pm 2) \times 10^{-4}$ [BEACH08 preliminary; PRL in prep]

Made possible by... Enormous HyperCP Dataset



HyperCP Spectrometer



...and Fast HyperCP DAQ System

≈20,000 channels of MWPC latches

≈100 kHz of triggers
...written to 32 tapes in parallel

HyperCP Collaboration

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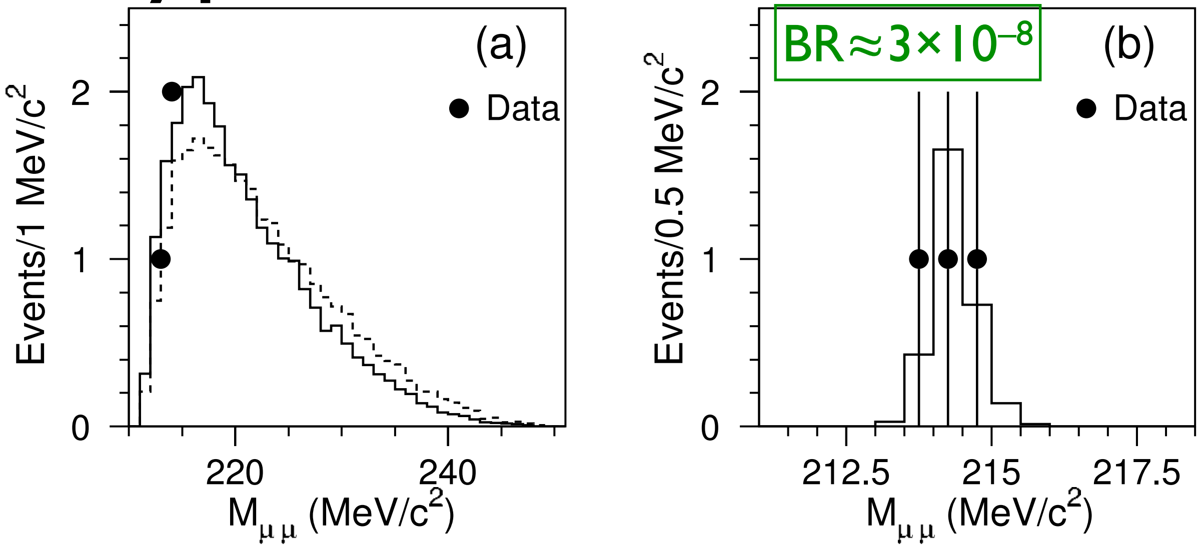
*co-spokespersons

$\Sigma^+ \rightarrow p\mu^+\mu^-$ Decay

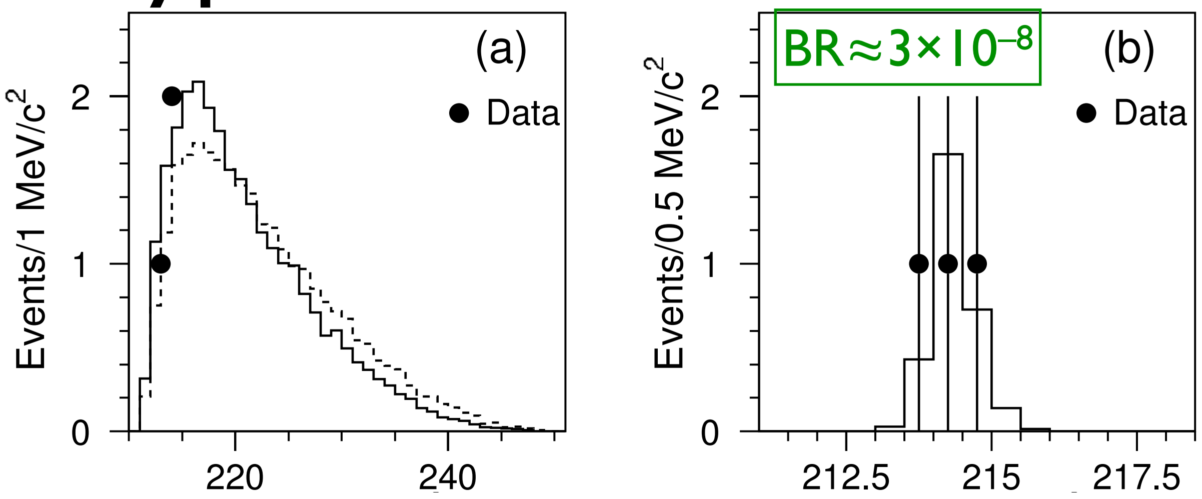
HyperCP also → 10^{10} Σ^+



≈2.4σ fluctuation of SM? or

- SUSY Sgoldstino?
- SUSY light Higgs?
- other pseudo-scalar or axial-vector state?

HyperCP also → 10^{10} Σ^+ $\Sigma^+ \to p\mu^+\mu^-$ Decay



≈2.4σ fluctuation of SM? or

- SUSY Sgoldstino?
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- other pseudo-scalar or axial-vector state?

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Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?

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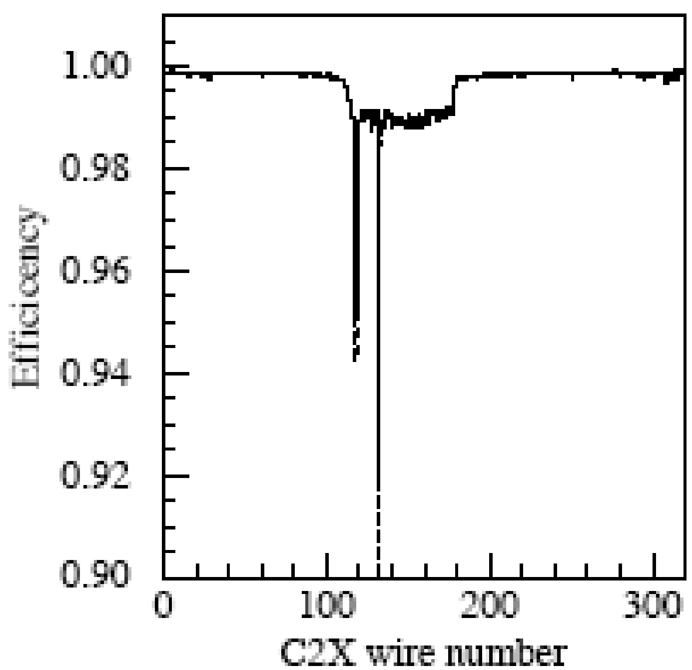
(Received 2 November 2006; published 22 February 2007)

The HyperCP Collaboration has observed three events for the decay $\Sigma^+ \to p\mu^+\mu^-$ which may be interpreted as a new particle of mass 214.3 MeV. However, existing data from kaon and B-meson decays provide stringent constraints on the construction of models that support this interpretation. In this Letter we show that the "HyperCP particle" can be identified with the light pseudoscalar Higgs boson in the next-to-minimal supersymmetric standard model, the A_1^0. In this model there are regions of parameter space where the A_1^0 can satisfy all the existing constraints from kaon and B-meson decays and mediate $\Sigma^+ \to p\mu^+\mu^-$ at a level consistent with the HyperCP observation.

How to follow up?

- Tevatron fixed-target is no more
- CERN fixed-target not as good (energy, duty factor)
- Main Injector, J-PARC not as good (same reasons)
- AND HyperCP was already rate-limited



- Big collider experiments can't trigger efficiently

➡ What else is there?

Low-Energy Antiprotons!

- Measurement history:

Experiment	Decay Mode	A_Λ	
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$	-0.02 $\pm$ 0.14	[P. Chauvat et al., PL 163B (1985) 273]
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		$(-6 \pm 2 \pm 2) \times 10^{-4}$	[BEACH08 preliminary; PRL in prep]

- Note: until ~2000, LEAR (CERN AD predecessor) had world's best sensitivity

➡ is $\bar{p}$ annihilation capable of further advance?

Antiproton Sources

- Fermilab Antiproton Source is world's most intense

Table 1: Antiproton energies and intensities at existing and future facilities.

Facility	$\overline{p}$ Kinetic Energy (GeV)	Stacking: Rate (10^{10}/hr)	Stacking: Duty Factor	Operation: Hours /Yr	Operation: $\overline{p}$/Yr (10^{13})
CERN AD	0.005 0.047	–	–	3800	0.4
Fermilab Accumulator:					
Tevatron Collider	8	>25	90%	5550	>150
proposed	≈ 3.5–8	20	15%	5550	17
FAIR ($\gtrsim 2018^*$)	1–14	3.5	15%*	2780*	1.5

…even after FAIR@Darmstadt turns on

➡ exceeds LEAR $\overline{p}$ intensity (<1 MHz) by >10 orders of magnitude!

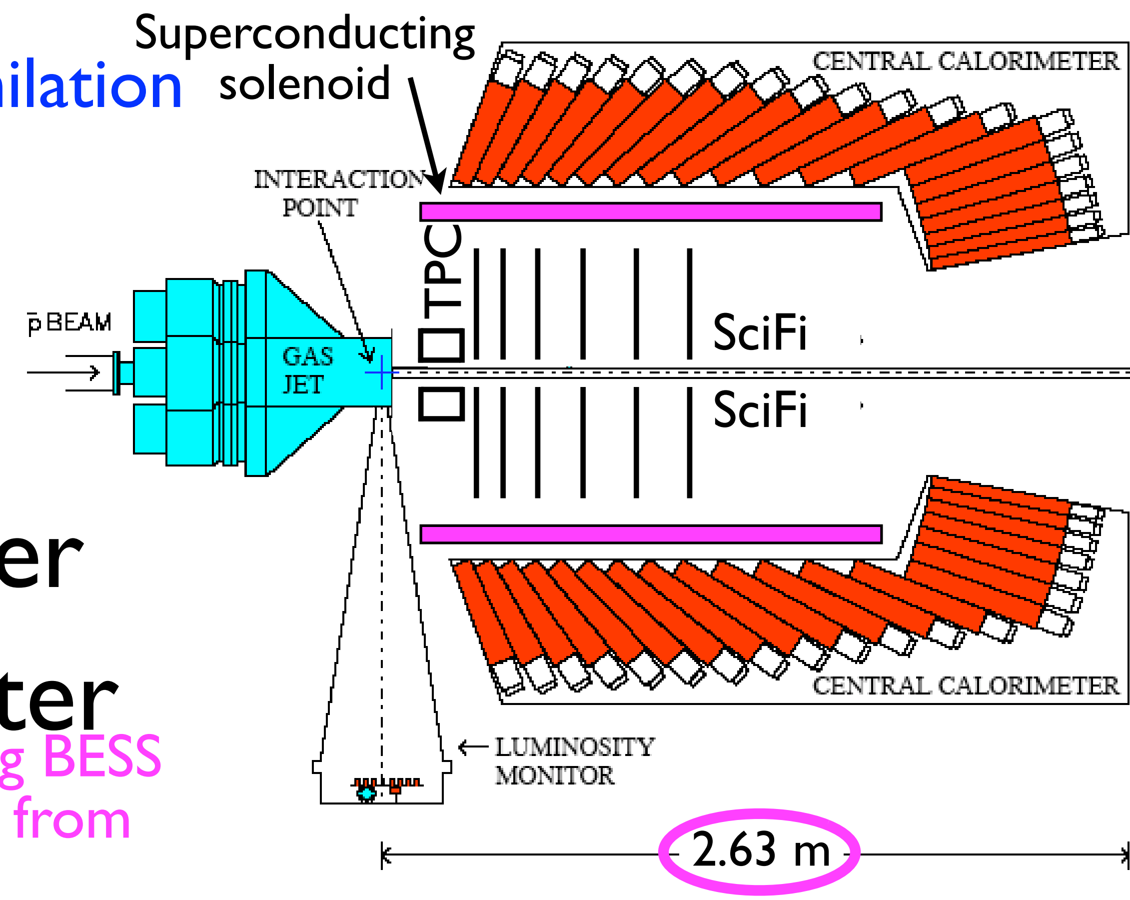
TAPAS

(The AntiProton Annihilation Specrometer)

Our proposal:

- Now that Tevatron finished,
  - Reinstall E760 barrel calorimeter
  - Add small magnetic spectrometer

[existing BESS magnet from KEK & SciFi DAQ from DØ



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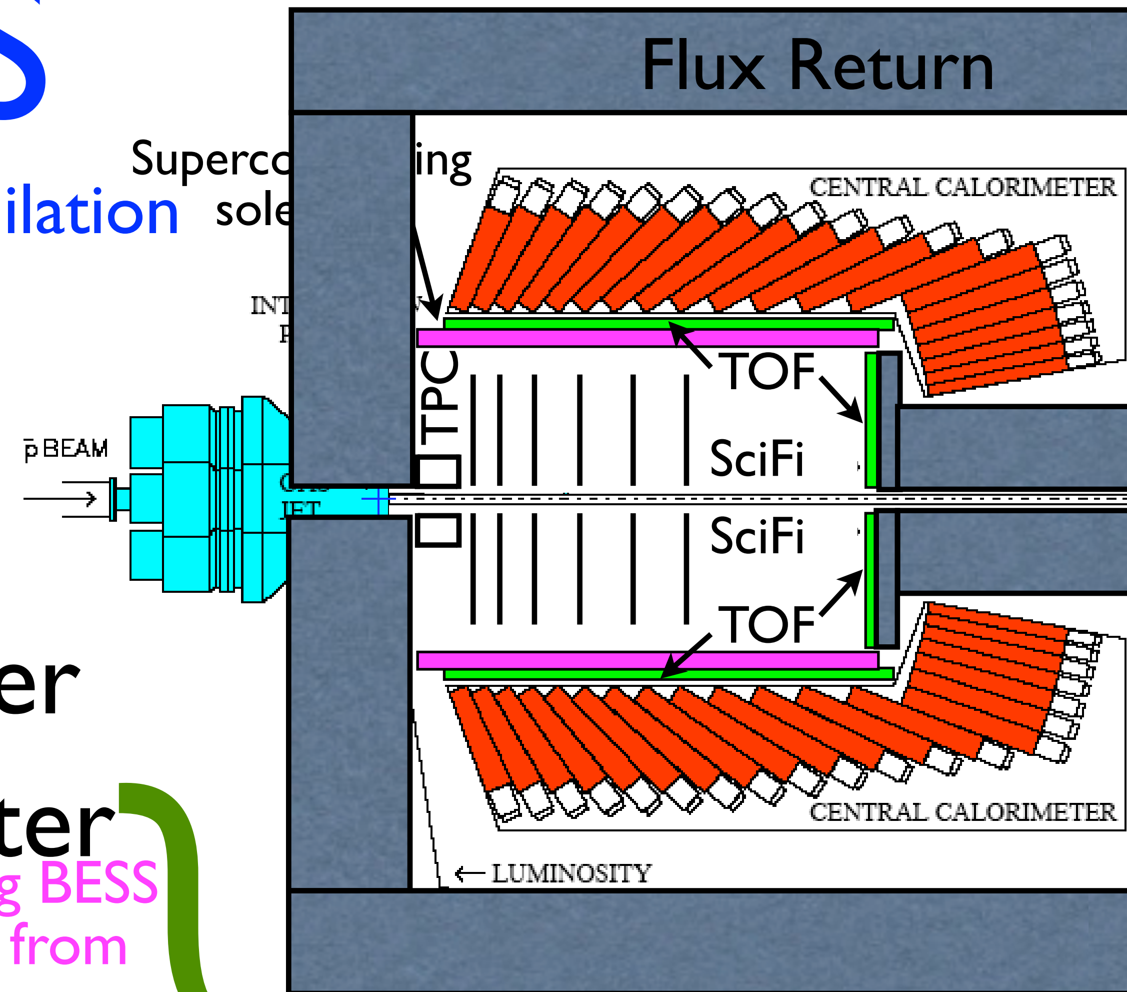


Our proposal:

- Now that Tevatron finished,
  - Reinstall E760 barrel calorimeter
  - Add small magnetic spectrometer
  - Add precision TOF system
  - Add thin targets
  - Add fast trigger & DAQ systems

[existing BESS magnet from KEK & SciFi DAQ from DØ & FNAL iron]

<$10M

  - Run $p_{\bar{p}}$ = 5.4 GeV/c ($2m_\Omega < \sqrt{s} < 2m_\Omega + m_{\pi^0}$) @ $\mathcal{L} \sim 10^{32}$ cm^{-2} s^{-1} (10 × E835)

➡ $\sim 10^8\ \Omega^- \bar{\Omega}^+$/yr + $\sim 10^{12}$ inclusive hyperon events! + possibly $\sim 10^{10}\ \Xi^- \bar{\Xi}^+$

What Can This Do?

- Observe many more $\Sigma^+ \to p\mu^+\mu^-$ events and confirm or refute new-physics interpretation

- Discover or limit $\Omega^- \to \Xi^-\mu^+\mu^-$ and confirm or refute new-physics interpretation

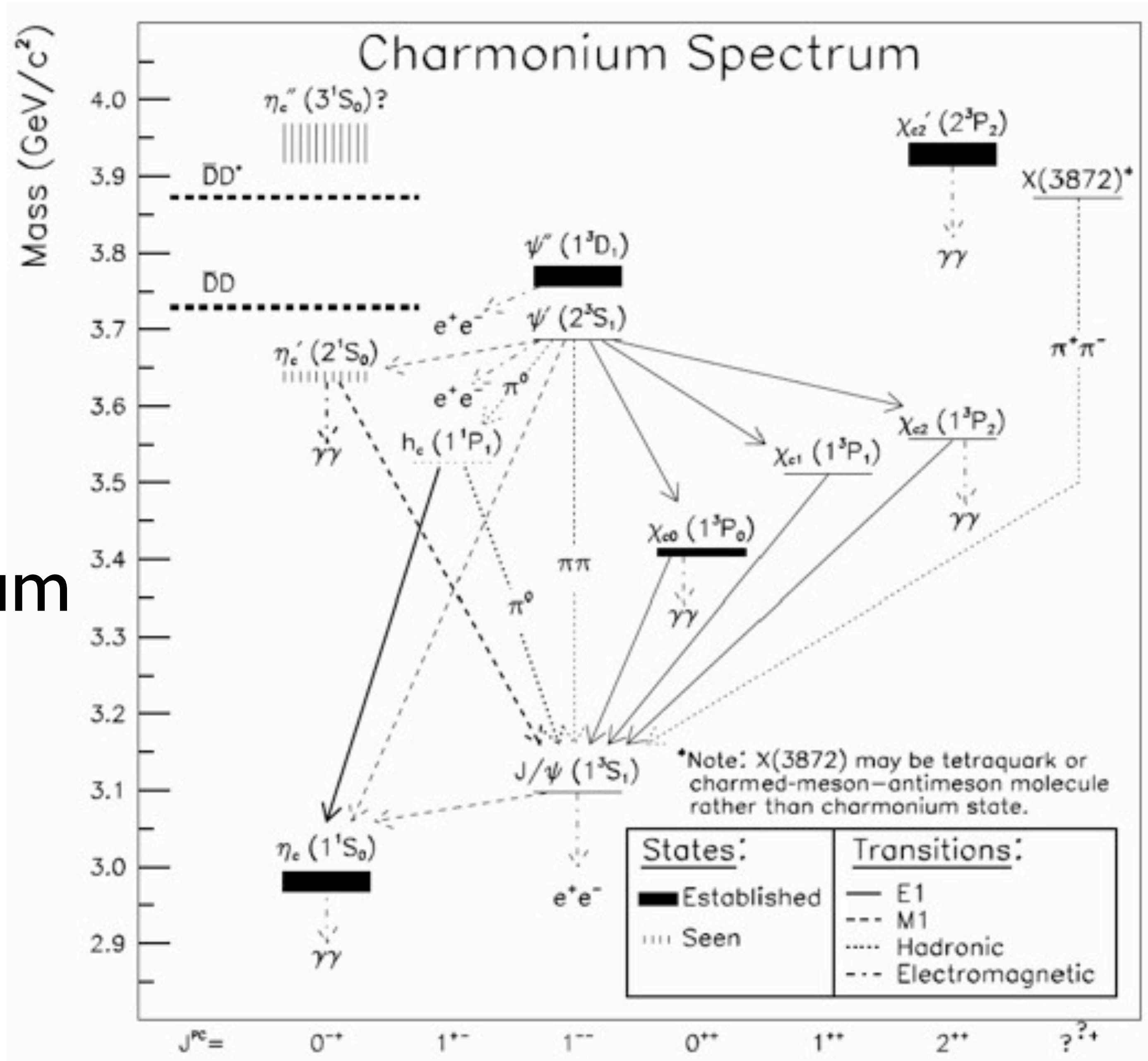
Predicted $\mathcal{B} \sim 10^{-6}$ if P^0 real

- Discover or limit CP violation in $\Omega^- \to \Lambda K^-$ and $\Omega^- \to \Xi^0\pi^-$ via partial-rate asymmetries

Predicted $\Delta\mathcal{B}/\mathcal{B} \sim 10^{-5}$ in SM, $\lesssim 10^{-3}$ if NP

What Else Can This Do?

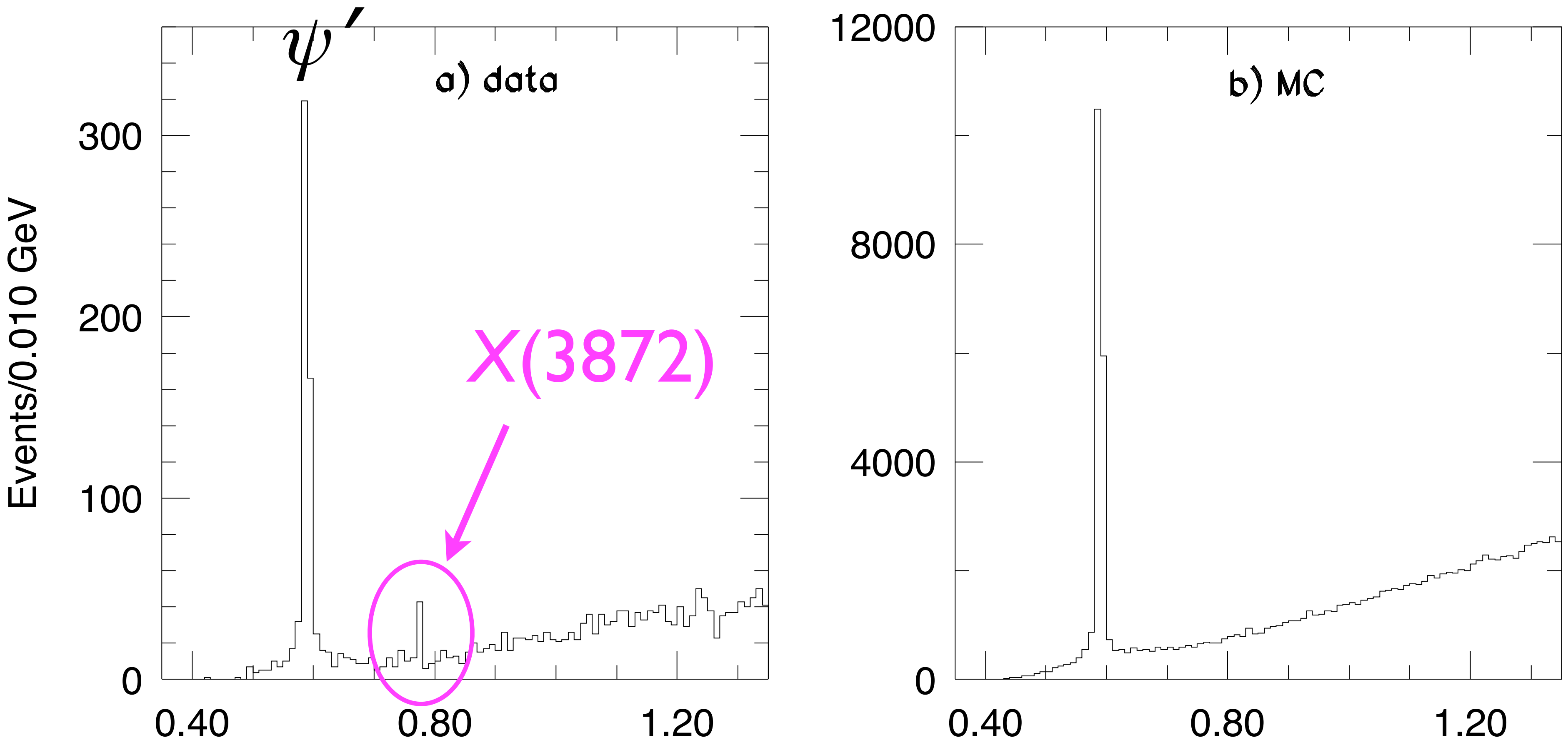
- Also good for "charmonium" ($c\bar{c}$ QCD "hydrogen atom"):
  - Fermilab E760/835 used Antiproton Accumulator for precise ($\lesssim$100 keV) measurements of charmonium parameters, e.g.:
    - best measurements of η_c, χ_c, h_c masses, widths, branching ratios,...



- $\bar{p}p$ produces *all* $c\bar{c}$ quantum states (not just 1^{--}), unlike e^+e^-

What ^Else^ Can This Do?

- Belle, Aug. 2003: $B^{\pm} \longrightarrow X + K^{\pm}, X \longrightarrow J/\psi\,\pi^{+}\pi^{-}$



- Since confirmed by CDF, D0, & BaBar
- Not consistent with being charmonium state
- Very near $D^0\,\overline{D}^{*0}$ threshold ($\Delta mc^2 = -0.35 \pm 0.69$ MeV)

XYZ hadronic transitions

- Many new states : ?

Is a new form of matter being glimpsed???

State	EXP	M + i Γ (MeV)	J^{PC}	Dec[illegible] Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	$3871.2\pm0.5 + i(<2.3)$	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4\pm0.7^{+1.2}_{-2.0}$ $3875.6\pm0.7^{+1.4}_{-1.5}$		$D^0 D^0 \pi^0$	B decays
Z(3930)	Belle	$3929\pm5\pm2 + i(29\pm10\pm2)$	2^{++}	$D^0 D^0$, $D^+ D^-$	$\gamma\gamma$
Y(3940)	Belle BaBar	$3943\pm11\pm13 + i(87\pm22\pm26)$ $3914.3^{+3.8}_{-3.4} \pm1.6 + i(33^{+12}_{-8} \pm0.60)$	J^{++}	$\omega J/\psi$	B decays
X(3940)	Belle	$3942^{+7}_{-6}\pm6 + i(37^{+26}_{-15}\pm8)$	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008\pm40^{+72}_{-28} + i(226\pm44^{+87}_{-79})$	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	$4156^{+25}_{-20}\pm15 + i(139^{+111}_{-61}\pm21)$	J^{P+}	D^*D^*	e^+e^- (recoil against J/ψ)
Y(4260)	BaBar Cleo Belle	$4259\pm8^{+8}_{-6} + i(88\pm23^{+6}_{-4})$ $4284^{+17}_{-16} \pm4 + i(73^{+39}_{-25}\pm5)$ $4247\pm12^{+17}_{-32} + i(108\pm19\pm10)$	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	$4324\pm24 + i(172\pm33)$ $4361\pm9\pm9 + i(74\pm15\pm10)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)
$Z^+(4430)$	Belle	$4433\pm4\pm1 + i(44^{+17}_{-13}{}^{+30}_{-11})$	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	$4664\pm11\pm5 + i(48\pm15\pm3)$	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

What $_\wedge^{\text{Else}}$ Can This Do?

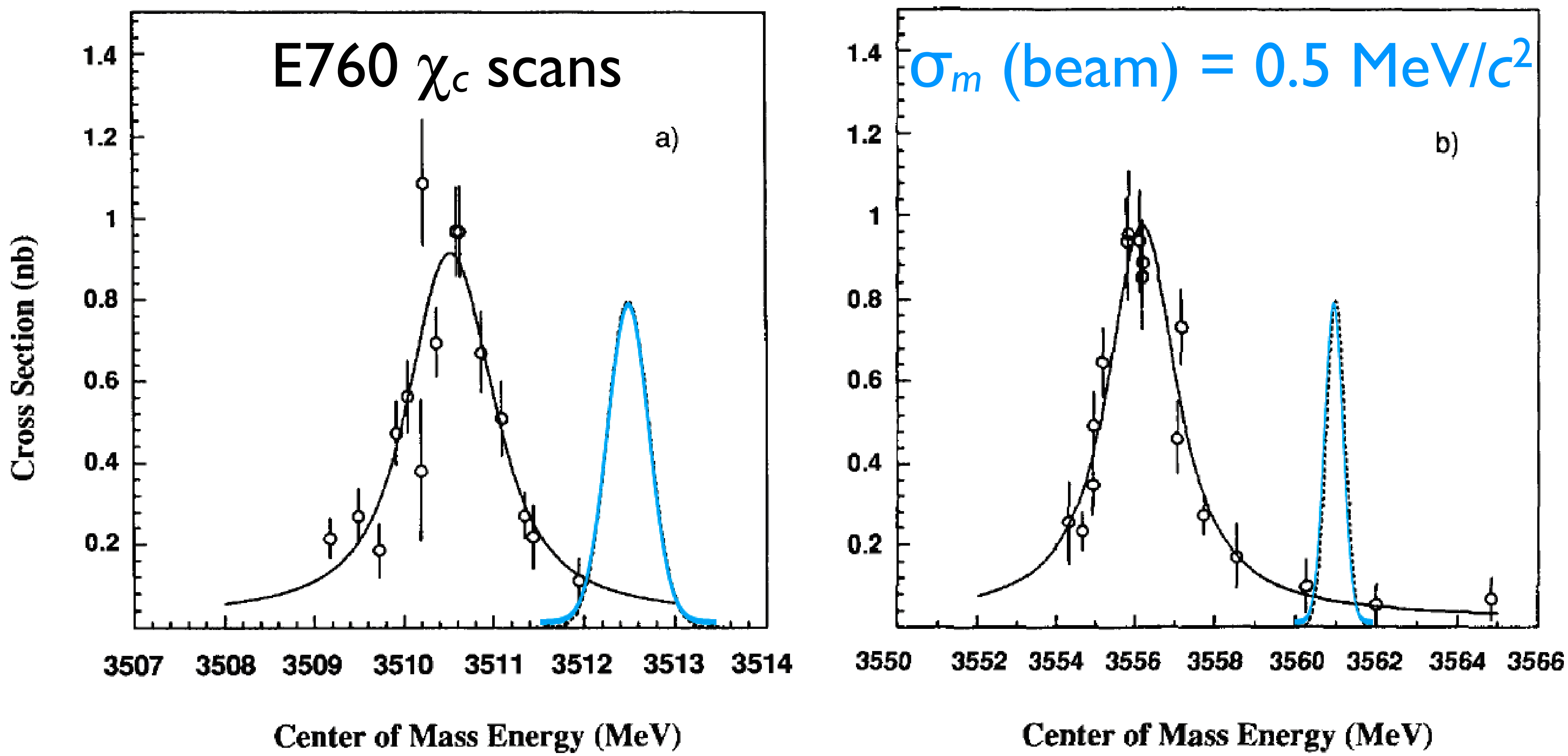
- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$

- $X(3872)$ of particular interest because it may be the first meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

➡ need *very* precise mass measurement to confirm or refute

➡ $\bar{p}p \to X(3872)$ formation *ideal* for this...

Example: precision $\bar{p}p$ mass & width measurements



- The beam is the spectrometer! $\rightarrow \begin{cases} \delta m(\chi_c) \approx 0.1 \pm 0.02 \text{ MeV}/c^2 \\ \delta\Gamma(\chi_c) \approx 0.1 \pm 0.01 \text{ MeV}/c^2 \end{cases}$
- The experiment is just the detector.

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- Much interest lately in new states observed in charmonium region: $X(3872)$, $X(3940)$, $Y(3940)$, $Y(4260)$, and $Z(3930)$
- $X(3872)$ of particular interest because it may be the first meson-antimeson ($D^0\,\overline{D}^{*0}$ + c.c.) molecule

➡ need *very* precise mass measurement to confirm or refute

➡ $\bar{p}p \to X(3872)$ formation *ideal* for this...

- Plus other *XYZ*, charmonium measurements, etc...

What ^Else Can This Do?

Charm!

PHYSICAL REVIEW D **77**, 034019 (2008)

Estimate of the partial width for $X(3872)$ into $p\bar{p}$

Eric Braaten

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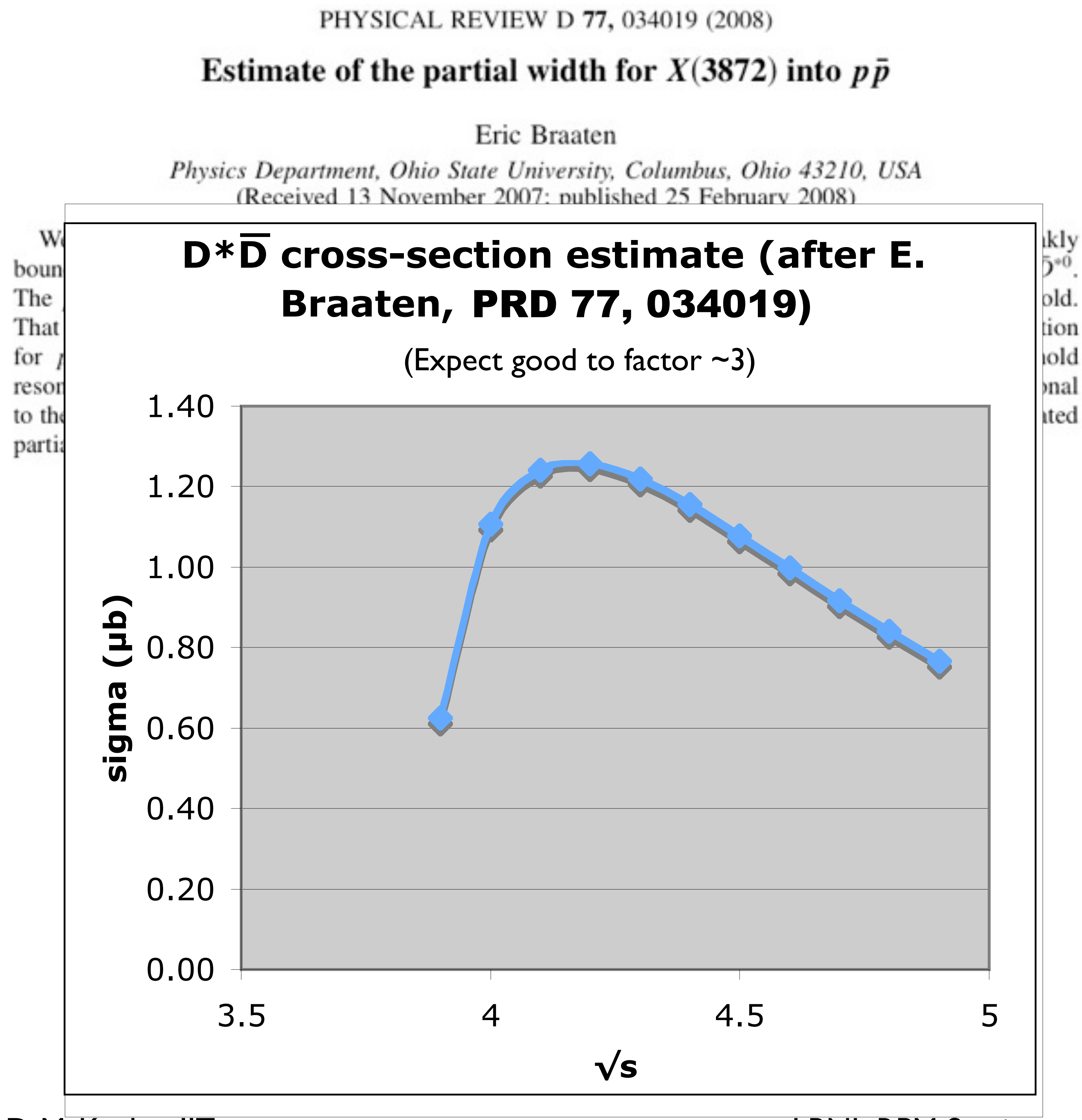
(Received 13 November 2007; published 25 February 2008)

We present an estimate of the partial width of $X(3872)$ into $p\bar{p}$ under the assumption that it is a weakly bound hadronic molecule whose constituents are a superposition of the charm mesons $D^{*0}\bar{D}^0$ and $D^0\bar{D}^{*0}$. The $p\bar{p}$ partial width of X is therefore related to the cross section for $p\bar{p} \to D^{*0}\bar{D}^0$ near the threshold. That cross section at an energy well above the threshold is estimated by scaling the measured cross section for $p\bar{p} \to K^{*-}K^+$. It is extrapolated to the $D^{*0}\bar{D}^0$ threshold by taking into account the threshold resonance in the 1^{++} channel. The resulting prediction for the $p\bar{p}$ partial width of $X(3872)$ is proportional to the square root of its binding energy. For the current central value of the binding energy, the estimated partial width into $p\bar{p}$ is comparable to that of the P-wave charmonium state χ_{c1}.

- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is $D^*\bar{D}$ molecule
  - extrapolates from K^*K data

Charm!


PHYSICAL REVIEW D **77**, 034019 (2008)

Estimate of the partial width for $X(3872)$ into $p\bar{p}$

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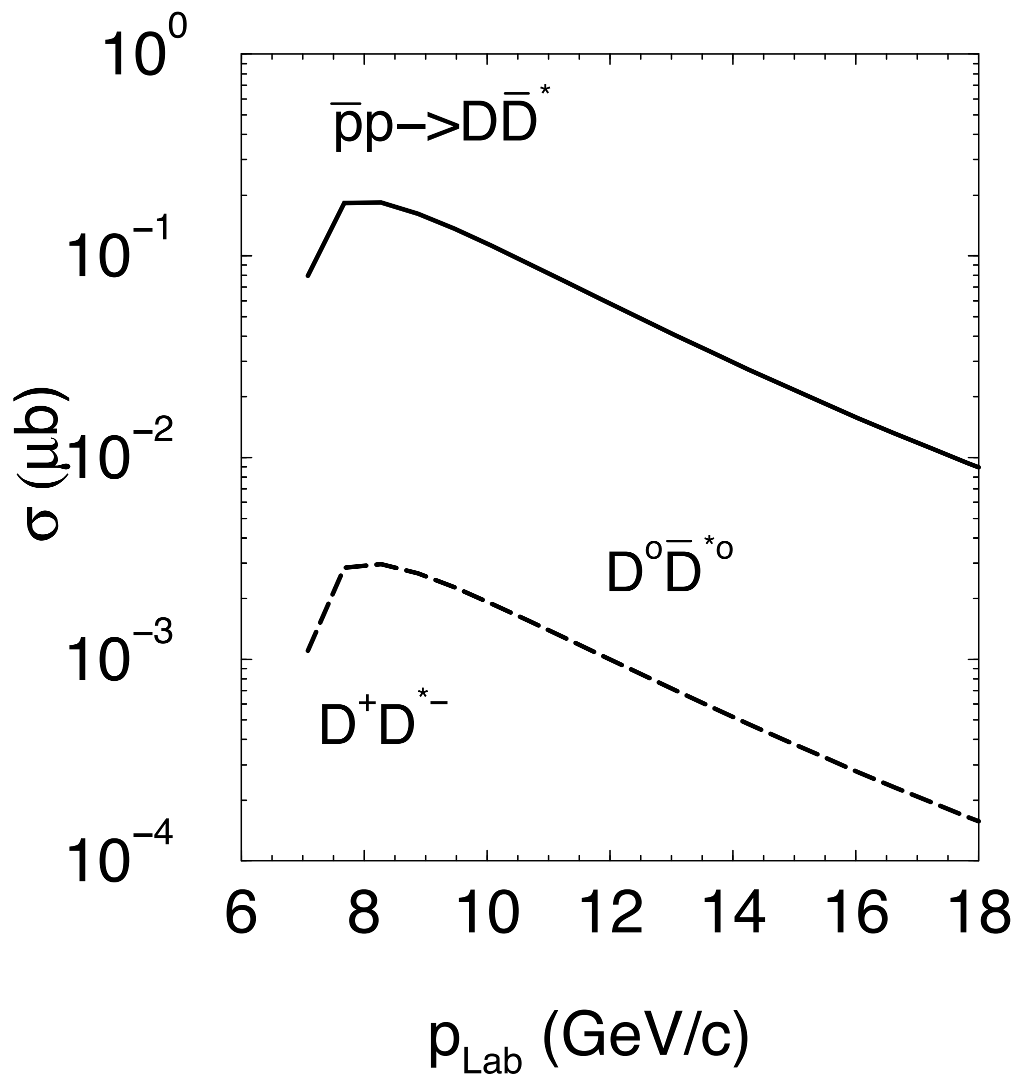
- E. Braaten estimate of $\bar{p}p$ $X(3872)$ coupling assuming X is $D^*\bar{D}$ molecule
  - extrapolates from K^*K data
- By-product is $D^{*0}\bar{D}^0$ cross section
- 1.3 μb → 5 ×10^9/year
- Expect efficiency as at *B* factories

Charm!

- Another approach (Regge model)



A. I. Titov and B. Kämpfer, Phys. Rev. C **78**, 025201 (2008)

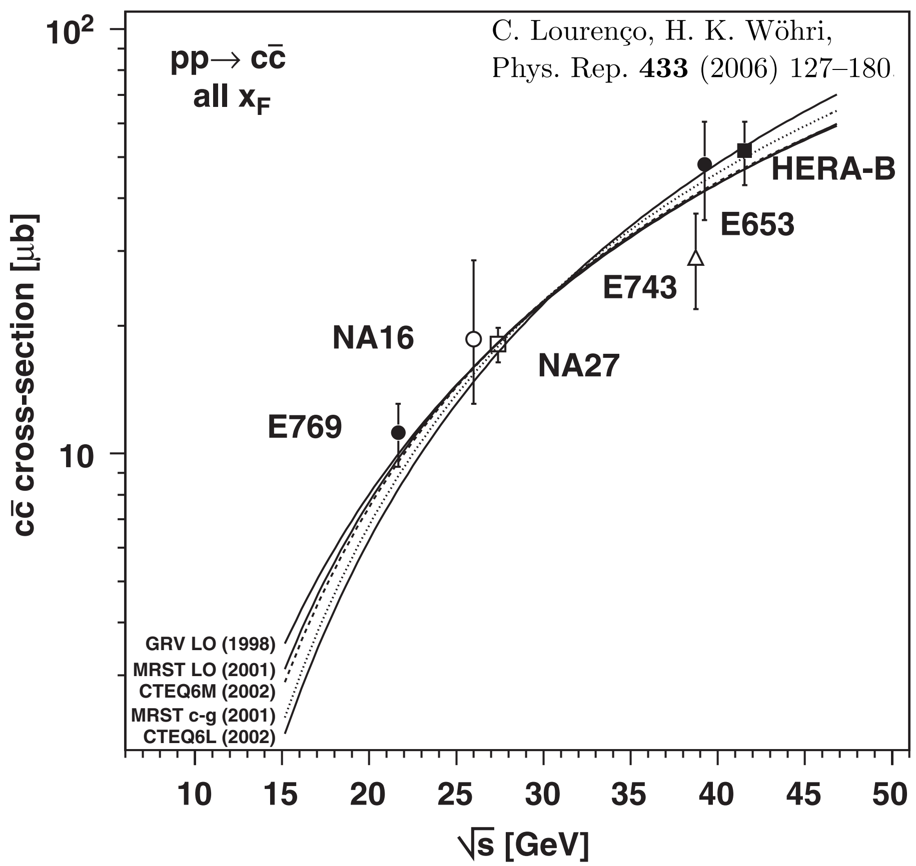
A. Titov, private communication

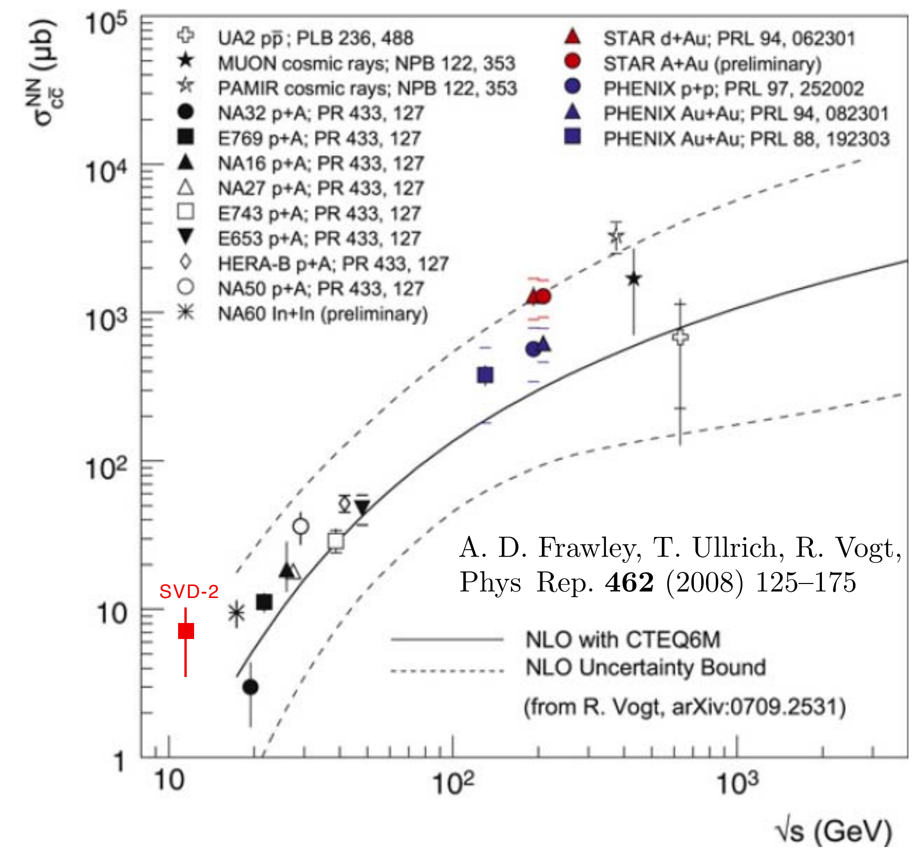
- Agreement within factor of 6

✓ not bad, considering it's low-energy QCD...

Charm!

- Other evidence?





REGISTRATION OF NEUTRAL CHARMED MESONS PRODUCTION AND THEIR DECAYS IN pA-INTERACTIONS AT 70 GeV WITH SVD-2 SETUP

(SVD-2 Collaboration)

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*Institute for High Energy Physics, Protvino, Russia**

S. Basiladze, S. Berezhnev, G. Bogdanova, V. Ejov, G. Ermakov, P. Ermolov, N. Grishin, Ya. Grishkevich, D. Karmanov, V. Kramarenko, A. Kubarovsky, A. Leflat, S. Lyutov, M. Merkin, V. Popov, D. Savrina, L. Tikhonova, A. Vischnevskaya, V. Volkov, A. Voronin, S. Zotkin, D. Zotkin, E. Zverev.
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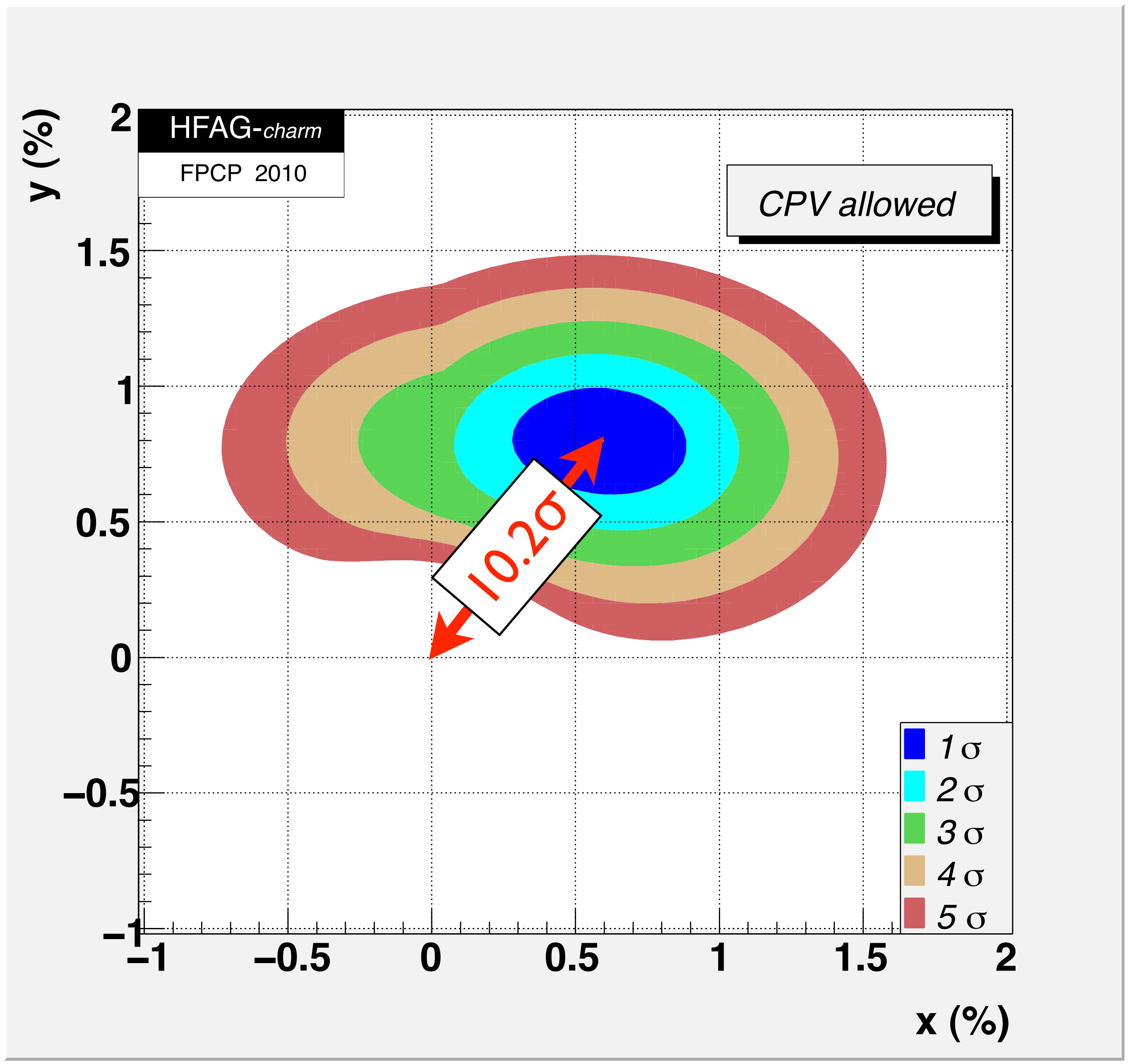
The results of data handling for SERP-E-184 experiment obtained with 70 GeV proton beam irradiation of active target with carbon, silicon and lead plates are presented. Two-prongs neutral charmed D^0 and $\bar{D}^0$ -mesons decays were selected. Signal / background ratio is (51±17) / (38±13). Registration efficiency for mesons was defined and evaluation for charm production cross section at threshold energy is presented: $\sigma(c\bar{c}) = 7.1 \pm 2.4(stat.) \pm 1.4(syst.)$ $(\mu b/nucleon)$.

- Hard to predict size of 8 GeV $\bar{p}$ cross section

⇒Need to measure it!

Charm!

- *What's so exciting about charm?*
  - D^0's mix! (c is only up-type quark that can)

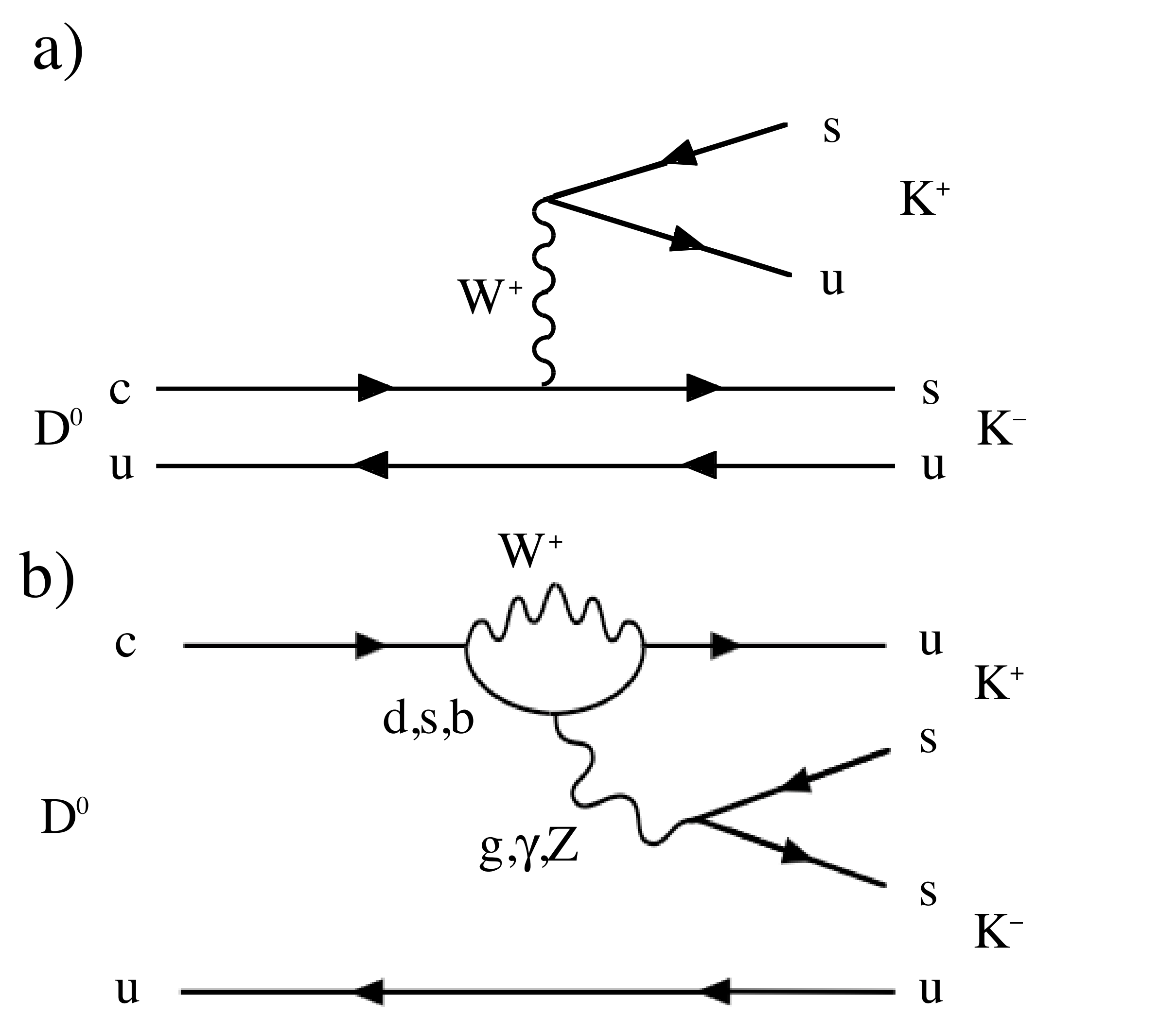


- *Big question:*
  New Physics or old?

Charm!

- *What's so exciting about charm?*
  - D^0's mix! (c is only up-type quark that can)

Singly Cabibbo-suppressed (CS) *D* decays have 2 competing diagrams:



- *Big question:* New Physics or old?

➡ key is *CP* Violation! Possible in CF, DCS only if New Physics

- B factories have ~10^9 open-charm events
- $\bar{p}p$ may produce $>10^{10}$/y

➡ world's best sensitivity to charm CPV

Charm!

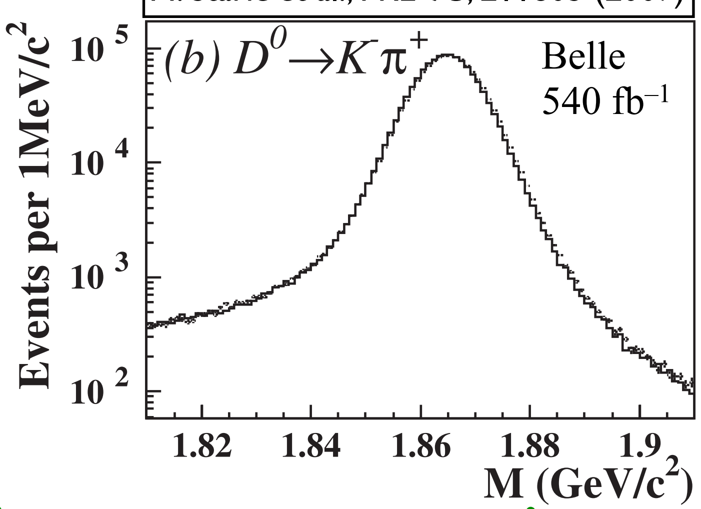
- Ballpark sensitivity estimate based on Braaten $\bar{p}p \to D^{*0}\bar{D}^0$ formula, assuming $\sigma \propto A^{1.0}$:

Quantity	Value	Unit
Running time	2×10^7	s/yr
Duty factor	0.8*	
$\mathcal{L}$	2×10^{32}	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Annual integrated $\mathcal{L}$	3.2	fb^{-1}
Target A (Ti)	47.9	
$A^{0.29}$	3.1	(based on H.E. fixed-target)
$\sigma(\bar{p}p \to D^{*+} + \text{anything})$	1.25–4.5	μb
# $D^{*\pm}$ produced	0.3–3 × 10^{11}	events/yr
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.677	
$\mathcal{B}(D^0 \to K^-\pi^+)$	0.0389	
Acceptance	0.45	(signal MC)
Efficiency	0.1–0.3	(MIPP & bkg MC)
Total	0.3–3 × 10^8	tagged events/yr

*Assumes ≈15% of running time is devoted to antiproton-beam stacking.

- Cf. 1.22 x 10^6 total tagged events at Belle:

M. Staric et al., PRL **98**, 211803 (2007)

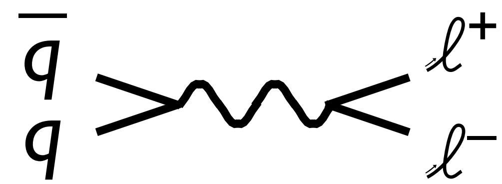


- Such subtle effects as charm CPV will require independent confirmation
  - LHC*b*: similar statistics? But different, significant, systematics
  - Also competitive with (ca. 2021) "Super B factories"

What Else?

- QCD tests:
  - event shapes and distributions
  - intrinsic charm $q\overline{q}$ component in the nucleon?
- Search for new, exotic states of matter:
  - pentaquarks, gluonic hybrids, etc.
- Target-*A* dependence:
  - possible calibration for heavy-ion effects
- Drell-Yan electron-positron pair production:
  - can signal be distinguished from background?

$\bar{p}p$ Drell-Yan

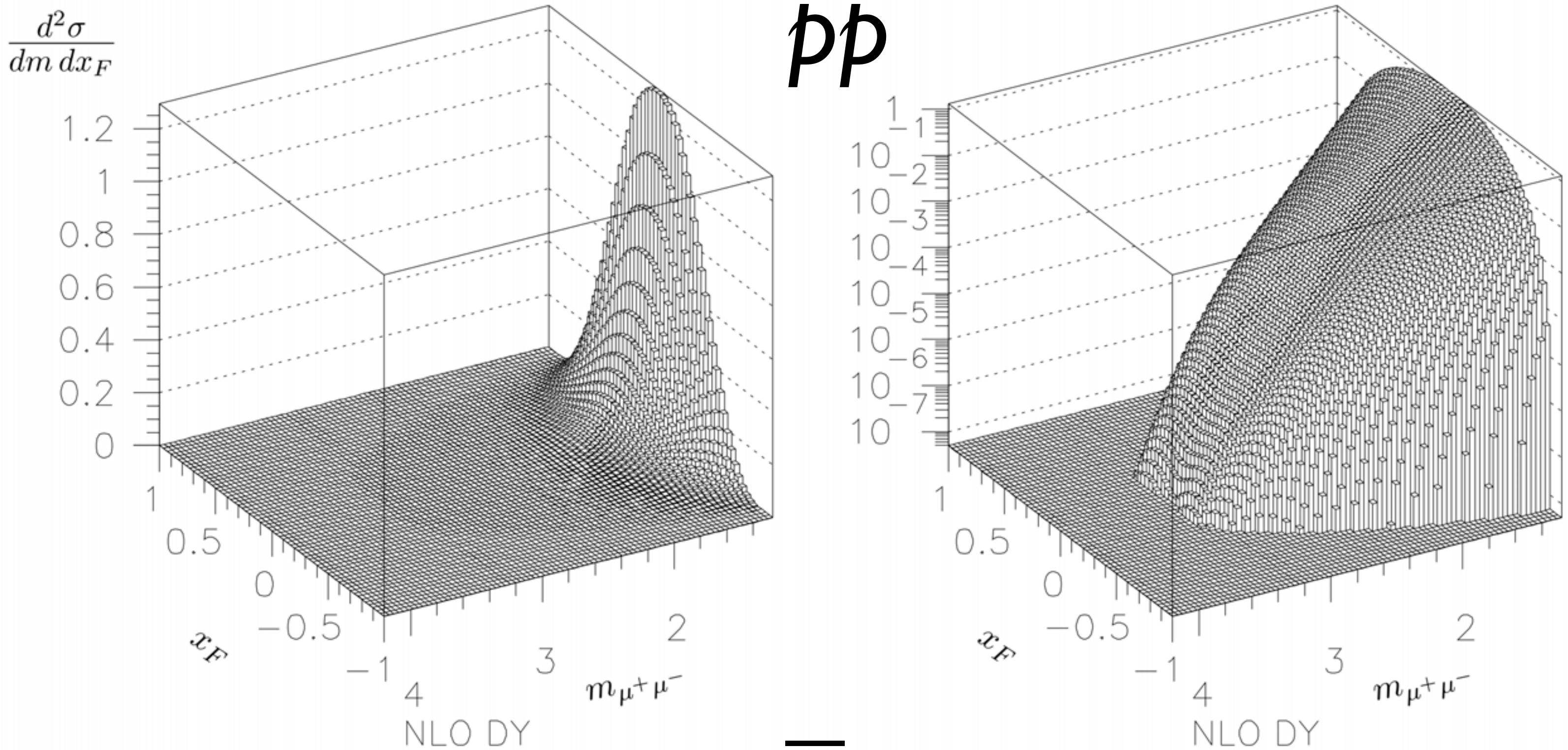


- $\ell^+\ell^-$ invariant-mass and momentum distributions sensitive to quark and antiquark distributions inside colliding protons and neutrons
- Global fits of nucleon structure suffer from significant tension among datasets
- $\bar{p}p$ or $\bar{p}A$ Drell-Yan can potentially add new constraints with very different systematics
  - "valence-valence" quark-antiquark annihilation

⇒ Can signal be dug out of the background???

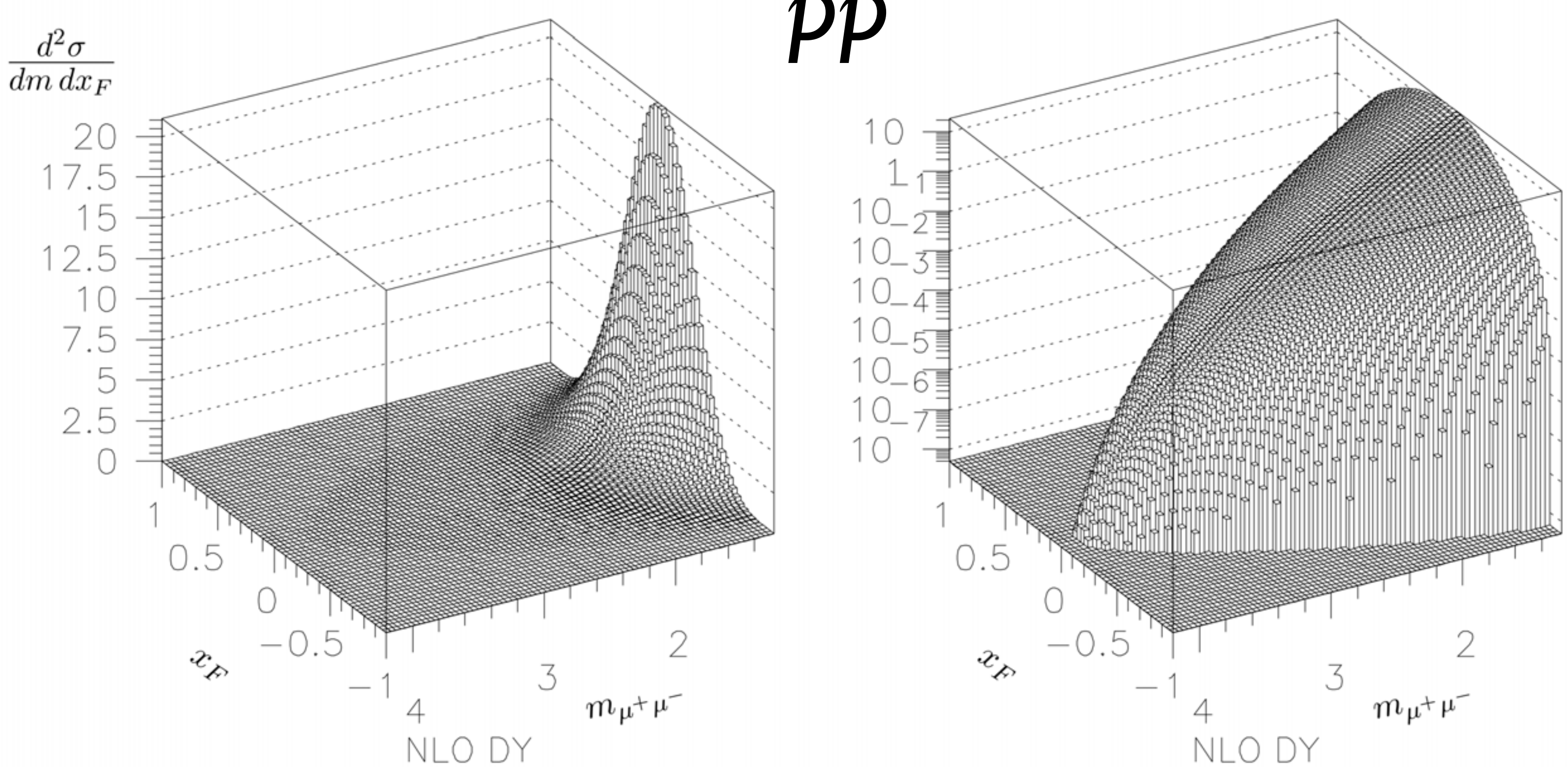
$\bar{p}p$ Drell-Yan

pp



valence-sea

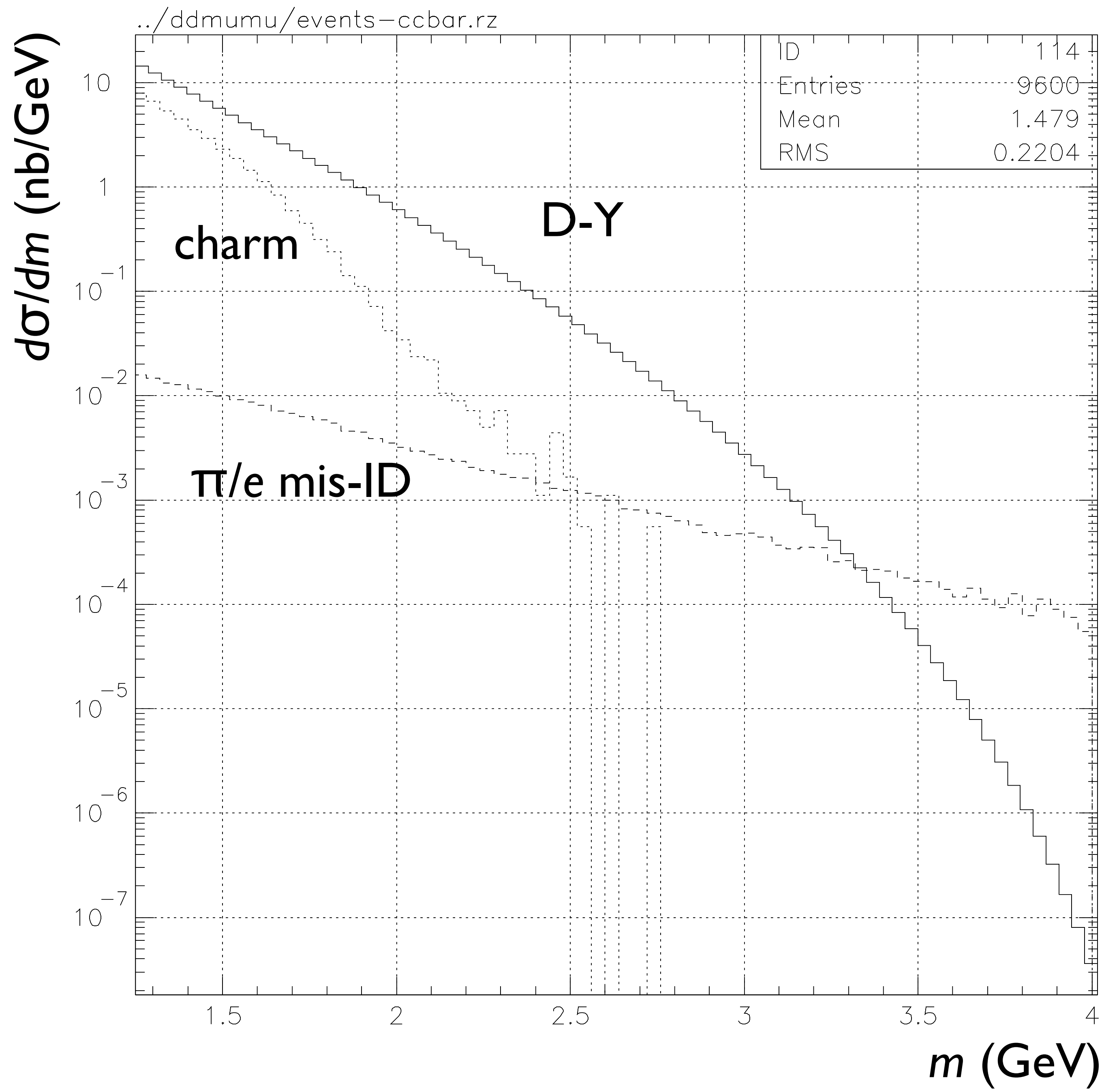
$\bar{p}p$



valence-valence

- increases cross section by factor ≈20

$\bar{p}p$ Drell-Yan



Compare signal with main backgrounds

- Low energy is advantageous:
  - ➡ less charm background
  - ➡ fewer pions to confuse
  - ➡ allows measurement in new kinematic region

$\bar{p}p$ Drell-Yan

- Medium Energy $\bar{p}$ Drell-Yan also studies
  1. Lam-Tung-relation violation in πN DY
  2. Boer-Mulders (quark spin–p_t correlation) function
  3. Weinberg angle (NuTeV anomaly) via FB asymmetry
  4. Threshold resummation (important for JLab as well as intrinsically interesting)

Breadth of Program

- *Partial* list of physics papers/thesis topics:

General	
1	Particle multiplicities in medium-energy pbar-p collisions
2	Particle multiplicities in medium-energy pbar-N collisions
3	Total cross section for medium-energy pbar-p collisions
4	Total cross section for medium-energy pbar-N collisions
Charm	
5	Production of charm in medium-energy pbar-p collisions
6	Production of charm in medium-energy pbar-N collisions
7	A-dependence of charm production in medium-energy pbar-N collisions
8	Associated production of charm baryons in medium-energy pbar-N collisions
9	Production of charm baryon-antibaryon pairs in medium-energy pbar-N collisions
10	Measurement of D0 mixing in medium-energy pbar-N collisions
11	Search for/Observation of CP violation in D0 mixing
12	Search for/Observation of CP violation in D0 decays
13	Search for/Observation of CP violation in charged-D decays
Hyperons	
14	Production of Lambda hyperons in medium-energy pbar-p collisions
15	Production of Sigma0 in medium-energy pbar-p collisions
16	Production of Sigma- in medium-energy pbar-p collisions
17	Production of Xi- in medium-energy pbar-p collisions
18	Production of Xi0 in medium-energy pbar-p collisions
19	Production of Omega- in medium-energy pbar-p collisions
20	Production of Lambda Lambdabar pairs in medium-energy pbar-p collisions
21	Production of Sigma+ Sigmabar- pairs in medium-energy pbar-p collisions
22	Production of Xi- Xibar+ pairs in medium-energy pbar-p collisions
23	Production of Omega- Omegabar+ pairs in medium-energy pbar-p collisions
24	Rare decays of Sigma+
25	Rare decays of Xi-
26	Rare decays of Xi0
27	Rare decays of Omega-
28	Search for/Observation of CP violation in Omega- decay
Charmonium	
29	Production of X(3872) in medium-energy pbar-p collisions
30	Precision measurement of X(3872) mass, lineshape, and width
31	Decay modes of X(3872)
32	Limits on rare decays of X(3872)
33	Production of other XYZ states in medium-energy pbar-p collisions
34	Precision measurement of the eta_c mass, line shape and width
35	Precision measurement of the h_c mass, line shape and width
36	Precision measurement of the eta_c' mass, line shape and width
37	Complementary scans of J/psi and psi'
38	Precise determination of the chi_c COG
39	Production of J/psi and Chi_cJ in association with pseudoscalar meson(s)

- TAPAS could maintain hadron physics at post-Tevatron Fermilab, multiplying physics output several-fold

Cost Estimate

- TAPAS is *very* cost-effective (by HEP standards):

Item	Cost (k$)	Contingency (k$)
Targets	430	160
Luminosity monitor	60	20
Scintillating-fiber tracking system	1,820	610
Time-of-Flight system	500*	500
Triggering	1,390	460
Data acquisition system	490	153
Infrastructure	1,350	550
TOTALS	6,040	2,450

- Thanks to: existing calorimeter, solenoid, SciFi readout system, trigger & DAQ electronics

Summary

- Best experiment ever on hyperons, charmonia, and charm may soon be feasible at Fermilab
  - possibly world's most sensitive study of charm mixing, charm & hyperon CPV & rare decays, + unique $\bar{p}$ DY
- Existing equip't enables quick, cost-effective effort
  - could start data-taking by 2014
- Preserves options for antihydrogen experiments
  - CPT, gravity tests
- World's best $\bar{p}$ source offers simple way to broad physics program in pre-Project X era

➡ Can Oddone's mind be changed?

Can you help???